A consideration of various factors affecting the net duty of irrigation water

By

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THESIS

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Letter of Transmittal

Prof. Charles Derleth, Jr.,
Dean of the College of Civil Engineering,
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Dear Sir:

In accordance with the regulations of the College of Civil Engineering, I herewith beg to submit to you for your approval my Thesis for the degree of Master of Science.

I remain, Sir,

Yours faithfully,

Philip R. Bisschop.

Berkeley,
April 30th, 1921.

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CHAPTER I

INTRODUCTION

It is well recognized that, regardless of the crop irrigated, a proper knowledge of the duty of water is essential to both the Farmer and the Engineer. Such, especially, is the case in newly developing irrigated and irrigable districts. With the growth and development of the irrigated sections the question of advantageously and economically using the limited amount of irrigation water is becoming more and more apparent. As the irrigable lands become more settled, more frequently is it asked just how much water is necessary to produce a good crop, and under what conditions of irrigation can the largest returns per acre foot of water as well as per acre be expected.

In South Africa especially, in its present period of development, is it essential that more definite information on which to base an answer to these questions, be obtained. It is a matter of extreme regret that up to the present no experiments, to determine the water Duty of our South African crops under the many varying climatic conditions, have as yet been undertaken.

It is essential to the farmer and irrigator to

have this information that he may make the arrangement for an adequate water supply, that he may avoid injury of his soil through the application of too much water, and that he may adjust to his land the amount available to him, so as to obtain the largest possible returns per acre foot of water applied. Further, he should have an understanding of the underground movement of the water after its application, that he may be sure, on the one hand, that excessive losses are not occurring through deep percolation, and, on the other hand, that the irrigation water is penetrating into the soil sufficiently deep to give proper nourishment to the feeding roots of his crop.

It is essential to the Engineer to have such information at his disposal in order that he may determine how large a canal to build to supply a definite area, or, having determined the quantity of water available and the cost of bringing it to the tract to be irrigated, he could not decide upon the practicability of his scheme because of his inability to determine how large an area the water supply is able to serve.

The Engineer, too, should have an accurate knowledge of the factors that influence the amount of water

used to mature a crop after its application to the soil. Such matters as the spacing of the furrows in orchard irrigation, the length of run and the corresponding most economical head of water to be used, frequency of application are of vital interest to the success of an irrigation scheme.

Again, we shall not be able to place on our statute books more logical laws concerning the proper use of water, or to enable our judges to render more satisfactory decisions in water disputes, until we have gathered a large amount of data, under properly controlled conditions, relative to the behaviour of water when brought upon soils for the production of crops.

The "duty of water" is a phrase which expresses the relationship existing between a given quantity of water and the area of land that it is made to serve. This amount may vary between the wasteful application of water on prepared lands in an unscientific way to the highly refined experimental methods as used for instance in Southern California, Where according to F. R. Adams "the water carried has the exceptional agricultural value of one thousand dollars per miner's inch."

It is therefore, in order to be more definite, perhaps advisable to use the phrase "the reasonable water requirements," which may be defined as "the use of that quantity of water which represents good practice when the character of the soil, topography of the land, value of the water, crop and other economic conditions are taken into consideration." It is in general that quantity of water with which the average farmer should obtain the best results without undue waste.

It is, of course, obvious that this quantity cannot possibly be permanently fixed and must necessarily vary not only with the physical and topographical conditions under which the water is applied, but also upon the economic conditions affecting the value of the water and the resultant crop.

It may be expressed as the number of acres that may be irrigated by a definite quantity of water, usually a second foot or cusec, flowing continuously throughout the irrigation season. The most commonly used unit is, however, the acre foot, which represents a volume of water equivalent to a depth of one foot on an area of one acre.

The Gross Duty for an entire System is made up

of the net Duty and the Loss in transmission.

The net Duty represents the actual amount of water delivered to the land and includes such losses as that by evaporation, percolation and waste, in addition to the actual amount that is absorbed by the plant.

The Gross Duty is the relation between the total irrigated area under the System and the amount of water diverted from the source of supply. The factors that influence the gross or entire duty of a Scheme are as many and as varied as the conditions under which an irrigation scheme operates. An attempt to summarize all these is shown in the following table:

FACTORS INFLUENCING THE DUTY OF WATER

- Factors which can be considered as fixed
  - Snowfall
    - Quantity
    - Distribution
  - Rainfall
    - Quantity
    - Distribution
  - Water
    - Clear
    - Fertilizing silt carried in suspension
  - Climate
    - Humidity
    - Wind movement
    - Sunshine
    - Length of Irrigation Season
    - Altitude
- Factors which may be modified
  - Losses in Storage
    - Seepage
    - Evaporation
  - Losses in Transmission
    - Seepage
      - 1. Distance from the stream to the land
      - 2. Soil through which the ditch is built
      - 3. Kinds of ditch
        - Lined & Unlined
        - Cross Section
    - Evaporation
      - Canal
      - Lateral
      - Field ditch
  - Irrigation Practice
    - Rotation or continuous use
    - Method of application
    - Head used
    - Waste water
    - Length of run
  - Cultivation
    - Dry mulch
    - Ordinary cultivation
    - Cover crop
  - Irrigable lands
    - Configuration of Surface
    - Soil and subsoil
    - Reparation of the land
    - Ground water level
  - Crops
    - Length of growing season
    - Diversified or not
- Factors which may be corrected
  - Faulty adjudication and Court Orders
    - Appropriation and granting of rights to more water than is needed
  - Methods of payment
    - Based on quantity rate
    - Based on flat rate

All these factors do much to increase or decrease the area that may be served by a given quantity of water. There remains, as a disturbing factor, the law that the more water that is added to a crop, the smaller will become the yield per unit of water served. This law of increasing water cost raises the question of whether the water should be used to obtain the largest possible yield per acre or whether moderate quantities shall be used to obtain the largest yield per acre foot of water served.

There is a depth of water for each type of land, crop and water conditions, which will provide a maximum profit. When water is added to a greater or less extent the amount of profit will vary accordingly. It is only with an increase of our knowledge of the duty of water that this point of "optimum" water, or of maximum beneficial use, can be determined for different crops and climatic conditions.

The following example will illustrate this point more clearly. (2)

A beet field is supplying beets to the factory at a contract price of five dollars per ton. The total cost of producing the crops, including interest on the in-

vestment, may be assumed to be thirty dollars per acre. Tabler I may be then constructed on the basis of the crop yield in the Utah experiments (see Bulletin 115, 116 and 117 Experiment Station) on the effect of varying quantities of water on the growth of crops.

30 acre inches applied over	Inches of water on each acre	Yield of beets per acre (tons)	Total yield of beets (tons)	Price paid for ton of beets	Gross income from beets	Cost per acre	Total cost	Net income from beets	Net income from acre
1 acre	30"	21.0	21	$5	$105	$60	$ 60	$45	$45
2 acres	15"	19.5	39	5	195	60	120	75	37.50
3 acres	10"	18.6	56	5	280	60	180	100	33.33
4 acres	7.5"	16.3	65	5	325	60	240	85	21.25

From the above, it will be seen, that the largest net aggregate income, was obtained when the 30 acre inches were spread over three acres. When spread over more or less land this amount decreased. The largest profit per acre was obtained with a thirty inch application, being seven and one-half dollars above that with the fifteen inch application. In the table the cost of the water has not been taken into account, vestment, may be assumed to be thirty dollars per acre. Table I may be then constructed on the basis of the crop yield in the Utah experiments (see Bulletin 115, 116 and 117 Experiment Station) on the effect of varying quantities of water on the growth of crops.

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and the question of what is the maximum economical yield will therefore be dependent on whether the surplus profit of seven and one-half dollars will compensate for the cost of the extra fifteen inches of water applied. Similarly in the fifteen and ten inches application, the maximum economical duty will be decided on whether the surplus profit of four dollars and thirteen cents will compensate for the cost of the extra five inches of water applied.

The differences between the net duty, the water requirement for maximum per acre yield and the water requirement for maximum economical per acre yield, should therefore be clearly kept in mind.

> "The conect water requirement for maximum per acre yield is that quantity of water which is necessary to produce a maximum yield per acre, when the losses of water by percolation, evaporation and waste, which can be controlled by skilful methods of irrigation and cultivation, have been eliminated.
>
> The water requirement for maximum economical yield from a limited water supply is that quantity of water which correctly used will give the maximum total net returns from a limited water supply and is dependent on the value of the water, the value of the land, the cost of irrigating, the cost of producing the crop and the value of the crop. The net duty merely represents the volume of water which is used according to the available water supply, the judgment and the skill of the

> irrigator. Where water is cheap and abundant throughout the irrigation season, the net duty will often exceed the water requirement for maximum per acre yield, because the consequent low price does not enforce careful irrigation and cultivation methods. Where water is scarce and therefore valuable, which is the usual case for a great part of the arid region, the net duty will approach the correct water requirement for maximum total economic yield."(6)

The amount of water that will produce the largest per acre yield of a certain crop is by no means at any time the most economic Duty. It becomes therefore imperative to undertake sufficient experiments to obtain this information for all the standard crops.

Theoretically, the aim in irrigation should be to obtain the highest possible efficiency out of every inch of rainfall and every supplementary acre inch of irrigation, and to use the least amount of the latter necessary to maintain a favourable moisture content throughout the main part of the growing season, while still permitting the soil to dry out sufficiently to mature the crop. Irrigation should be applied when the soil moisture content drops to near the wilting point, and in just a sufficient amount to raise the moisture content to the maximum usable water capacity of the soil throughout the root zone.

Proper irrigation supplies a favourable moisture condition and encourages the growth of feeding roots, bacterial activity, and the liberation of plant food. Improper irrigation checks these processes and often causes unfavourable soil temperature and drainage problems, or the leaching of plant food. Proper irrigation tends to produce optimum moisture content conditions. Again, there is always a tendency under irrigation to compact the soil and to exclude the air. It is exceedingly important, therefore, to practice rotation, including soil building crops which will offset this tendency of the soil to compact and make it practicable to maintain a high state of tilth with a high percentage of organic matter. It is the intention to discuss in this thesis these influences which may modify the net Duty of water, rather than the many, varied and complex factors, enumerated above, which go together to form the Gross Duty of an Irrigation System.

That it is well worth our time to give careful study and investigation to this particular phase of the question is borne out by the following general figures of the disposal of irrigation water after its application to the soil.

Surface waste		5--15	percent
Deep percolation losses		20--50	"
Soil evaporation	"	10--20	"
Total	"	35--85	"
Amount available for plant transpiration		65--15	"

It will be seen that even under the best of conditions, the losses will usually amount to thirty-five percent of the water applied.

> "While these losses appear high and while they can be reduced under proper methods of irrigation, the expense of their reduction may, in many localities, exceed the present value of the water saved. Where the losses are excessive, the best crops are usually not secured and it will pay to improve the method used and reduce the losses to reasonable amounts."(Harding)

Whilst it is unquestionable that the major part of this loss is due rather to the mechanical factors of the application of the water to the land--factors which even under the very best of conditions are often not practicable to modify--a greatly increased efficiency of the water should be obtained from a proper knowledge of the more theoretical considerations of the question. It is rather with this part of the problem to which this discussion will be limited. Any improvement on the practical

side is an entire local question, to be solved by each individual project according to the prevailing conditions. A discussion of this side of the question could at the very best only be most indefinite. On the other hand theoretical considerations lead to definite principles which if followed expeditiously should help to secure not only a higher increased Duty on existing schemes, but also give much more definite information as to the probable irrigable area under a projected scheme.

CHAPTER II

THE TEXTURE AND STRUCTURE OF THE SOIL

It is now perhaps universally recognized that the character of the soil has more influence upon the Duty of water, in the sense of the reasonable water requirement, than any other factor. It is the texture and structure of the soil which to a large extent determines the amount of water that is lost by deep percolation, carrying with it below the root zone a considerable amount of valuable plant food. It is also the texture and structure of the soil which determines the lateral movement of the water for equal distribution under furrow irrigation, as well as the upward movement with its consequent evaporation. A brief survey of some of the importance characteristics of soils will help in obtaining a clearer perspective of the various influences to which irrigation water is subjected. Arbitrarily speaking, soils may be divided into seven grades or "separates", comprising fine gravel, coarse sand, medium sand, fine sand, very fine sand, silt and clay. This grouping, established by the United States Bureau of Soils, is dependent on the size or tecture of the soil particles, varying from 2--1 mms. in diameter for fine gravel to diameters below .005 mms. for clay.

As these groups vary in size they exhibit properties, especially in regard to the moisture content, which vary widely, which again are imparted to the soil of which they are members.

These clay particles are very minute, jagged and angular in outline. They are highly plastic, and when rubbed together become sticky and impervious. They shrink on drying and re-expand on being melted. The finer part of the clay consists of colloids, which, because of their fineness of division, exhibit certain well defined properties, of which absorption of moisture and high plasicity and cohesion are the most important. Silt exhibits the same qualities, but to a much less marked extent. The presence of clay imparts to it a heavy texture, with a tendency to very slow water and air movement. Its water holding capacity is high. The soil is highly plastic, becomes sticky when too wet and hard and cloddy when too dry.

The sands and the gravels function more as separate particles. They are irregular and rounded, exhibit very low plasticity and cohesion and as a consequence are little influenced by changes in water content. Their water holding capacity is low, and because of the large individual size of the pore space the passage of water is rapid. In

regard to structure--or the arrangement of the soil particles in the soil--a wide variance is met as well.

It is a well known fact that the soil particles are not homogeneous in size; neither do all the particles function as simple grains, being gathered together in groups called granules or crumb structure. A small particle of soil may be made up of a number of very small grains placed in between somewhat larger particles, resulting in a reduction of the pore space. A soil having such restricted pore space is said to be in a puddled condition. The condition is detrimental to plant growth, impeding the root development, but also preventing the circulation of air and water; a most necessary function for plant growth.

On the other hand, when a soil is made up of complexes of soil granules an increased pore space will occur. There will therefore be a very wide range of pore space ranging for the different types of soils as shown by Table II.

TABLE II.

Percentage of Pore Space for Different Soils
(King)

Sandy soil	32.49
Loam	34.49
Heavy loam	44.15
Loamy clay soil	45.32
Clay loam	47.10
Clay	48.00
Very fine clay	52.94

The pore space in any of these soils is naturally subject to considerable fluctuation, especially in the surface soil, due to tillage and the amount of organic matter present. When, however, soils are in the physical condition for the best plant growth, it will be found that the finer the soil, the greater will be the pore space.

In a soil the pore space is occupied by water and air. If the water content is low, the pore space is large and vice versa. Thus the relationship of the aggregate pore space and the size of the individual spaces to the amount of contained air and water, to their movement through the soil, to root extension, to soil aeration, to

bacterial activity become apparent.

The factors which control the soil structure are plasticity and cohesion. As these increase, there is, with an excess of water, a tendency towards puddling. On the other hand, when too dry clodding will result. A diminution of these factors in heavy soils will give a better granulation of the soil particles.

Granulation is "nothing more or less than a condition brought about by the force exerted by a variable water film and the pulling and binding capacities of colloidal matter, operating at numberless localized foci. It is evident that any influence or change in the soil which will cause a greater localization of these forces will promote increased granulation." And since the optimum moisture condition of a soil for tillage is also fortunately the optimum condition for plant growth, careful attention should be paid to the effect of alternate wetting and drying of the soil, ploughing, freezing and thawing, and the addition of organic matter and lime, upon the granulation of the soil particles.

The moisture contained in the soil may be hygroscopic, capillary and gravitational. Hygroscopic moisture is the moisture which a soil dried by artificial heat will

absorb from a saturated atmosphere. Due to the absorptive capacity of the soil particles, this moisture will exist round the particles in the form of a thin film, being held partly by the surface tension of the film and partly by the molecular attraction of the moisture molecules. The amount of hygroscopic moisture increases with the total surface exposed or the fineness of the particles. Any practice that will increase the colloidal material--the humous, colloids being very susceptible to an increase--the higher will be the percentage of hygroscopic moisutre. This is well illustrated in Table III.

TABLE III

Hygroscopic Capacity of Various Soils (4)

Soil	Percent clay remaining in suspension after standing 24 hours	Hygroscopic Water expressed in percent
15 clays	31.97	10.45
7 clay loams	17.15	6.06
9 loams	12.06	5.18
5 sandy loams	7.39	2.50
4 sands	2.93	2.21

Hygroscopic water is held so rigidly to the soil particle that it is in no way available to the plant. As this zone

increases, due to an increase in the moisture content, a thickness of moisture film is reached in which the molecular movement is perfectly free and unimpeded. These two zones, one in which capillary movement is more or less free, and the other a comparatively thin film in which molecular movement keeps the moisture attached to the soil particle, gradually merge into one another.

As more water is added and the film thickness round the soil grains, the outer layers are held with decreasing force, and a point is reached at which plants are able to procure all the moisture needed. At this point, according to Dr. Widtsoe, the film water is held so loosely that it moves freely from soil particle to soil particle, being termed the Lento capillary point. Above this point the water is readily available to plants and constitutes the main supply of water for plants under irrigated conditions.

Hence the following coefficients are well established (1) The hygroscopic coefficient is the percent of moisture, based on the dry weight of a soil, that a dry soil will absorb when placed in a saturated atmosphere. (2) The wilting coefficient is the percent of moisture, based on the dry weight of the soil, which remains in the soil when the plant has reached a condition of permanent wilting.

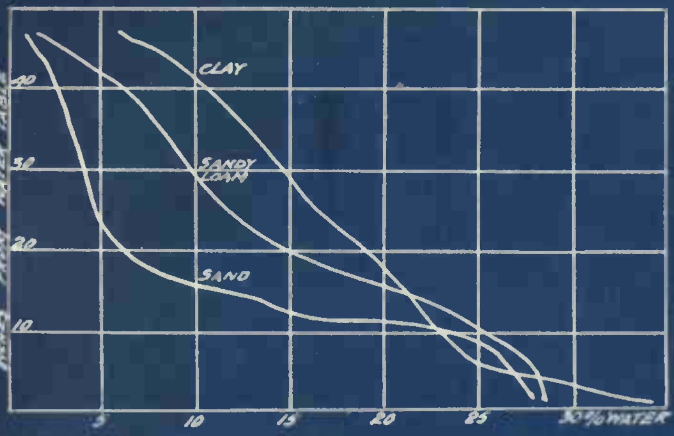

FIG. I

Diagram showing the distribution of moisture in capillary columns of different textures.
LYON FIPPIN BUCKMAN

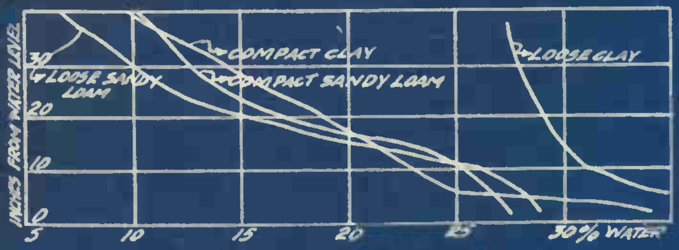

FIG. II

Diagram showing the effect of a compaction upon the moisture distribution in capillary columns.
LYON FIPPIN BUCKMAN

Diagram showing the forms of water in the soil and their relationship to the plant.

FIG III

For successful plant growth, the moisture content should never be allowed to approach the wilting coefficient. According to the researches of Briggs and Shantz the hygroscopic coefficient is about .68 as great as the wilting coefficient or the wilting coefficient is about 1.50 times the hygroscopic coefficient.

The finer the texture of a soil, the greater is the number of angles between the particles in which a film of capillary water may be held; also, the actual amount of surface exposed by the particles is immensely larger than in a coarse soil. Due to these two conditions a soil of fine texture will contain considerably more capillary water than one of which the texture is coarse. See Fig. I.

The structure of the soil, or the arrangement of the particles, will become a factor in the capillary capacity in so far as it affects the amount of surface exposed to capillary action. Hence the granulation of a clay soil, by producing a crumb structure and by increasing the exposed surface, tends to increase its water holding capacity. On the other hand the compacting of a sand, by increasing both the effective surface as well as increasing the possible number of angles for capillary concentration, will have the same effect. See Fig. II. Organic matter has a great capil-

lary capacity. Not only its porosity but also its colloidal content exerts a very high affinity for capillary water.

Capillary water moves from a wetter or thicker moisture film to a drier or thinner water film. The water will rise to a greater height on a fine textured soil tham on a coarse textured soil, although its rate of progress is much greater in the latter. Lyon and Fippin give the following Table.

TABLE IV

Capillary Rise in Inches for Different Lengths of Time (11)

Soil	¼ hr	1 hr	2 hrs	1 day	3 days	8 days	13 days	19 days
Silt and very fine sand	2.7	4.7	7.0	20.0	30.0	45.0	52.0	56.0
Very fine sand	7.6	10.0	12.4	21.0	23.0	26.0	27.5	28.5
Fine sand	9.0	9.5	10.0	11.6	13.0	14.3	15.2	16.0
Coarse and medium sand	5.8	6.0	6.3	7.5	9.0	10.0	11.5	12.5
Fine gravel	4.0	5.0	5.3	6.4	8.0	9.0	10.0	10.8

With a further increase in the water content, a point will be reached when new additions of water will simply slide off the existing film and be drawn off by gravity. Dr. Widtsoe has called this point the point of maximum capillary capacity. Any existing water above this is termed Gravitational water. See Fig. III. It moves slowly downward through the pores and tubes of the soil until it is all absorbed by the lower drier soil or until it communicates with the standing water table. When gravitational water begins to appear, an adverse condition to plant growth is obtained. The proper aeration of the soil is much hampered, the roots are deprived of their oxygen and toxic materials tend to accumulate. It is therefore evident that there must be some moisture condition in a soil which is best for the development of the plants, often termed the optimum content.

The total range of available moisture does not of course represent this condition. In practice the moisture content will fluctuate considerably, forty to sixty percent of the pore space being considered essential for best growing conditions. It should be the object of every irrigator to apply just such an amount of water to his land as to bring the water moisture content as high as

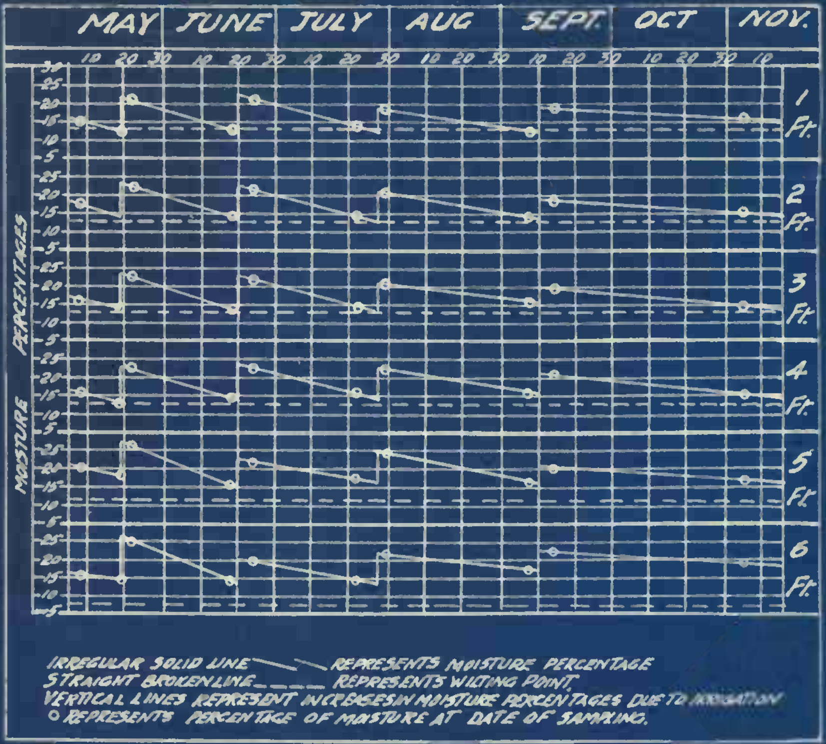

Diagram showing Seasonal variation in soil moisture percentage, Wigno alfalfa field, Los Molinos 1914. (ADAMS)

FIG IV

possible without experiencing deep percolation losses, and at such periods that the minimum water content just before irrigation does not approach the wilting coefficient. The extent to which this is achieved in practice is illustrated by the experiments of F. R. Adams on Sacramento Valley Soils. Fig. IV shows the percentages of soil moisture in a fine sandy loam soil before and after irrigation for various depths. The diagram showsthat the moisture percentage reached or closely approached the wilting point in the upper three feet of soil before each irrigation, but that it was well above the wilting point throughout the season in the third, fourth and fifth feet below the surface.

The results of a considerable number of experiments conducted on the moisture properties of soils under field conditions of irrigation are summarized in Table V.

TABLE V *(Harding)*

Character of soil	Usual average percent of total moisture		
	At wilting point	When irrigation is desirable	After irrigation when free to drain
Sandy soil	3	5	8
Sandy loam	5	9	13
Fine sandy loam	6	12	18
Loam	8	14	21
Silt loam	10	16	22
Light clay loam	13	17	22
Clay loam	14	18	22
Heavy clay loam	16	19	23
Clay	18	20	24

It is evident that, even after a heavy irrigation, the average percentage of water held in a soil to a depth of ten feet is far below the maximum capillary water content. Invariably only the top foot or often the top layer contains that quantity. With increasing depth, there is invariably a decrease in moisture content until about eight to fifteen feet, it is very little above the point of slow capillary

TABLE VI

Table showing the distribution of moisture after irrigation (Widtsoe)

Depth	Depth of Water Applied			In the Spring
	7.5 inches	5 inches	2.5 inches	
1	23.80	23.56	18.57	18.42
2	21.88	20.73	13.81	17.49
3	20.17	19.09	13.53	15.65
4	17.72	17.84	13.46	14.07
5	15.91	16.29	12.32	13.98
6	14.55	15.83	11.81	13.14
7	14.21	15.60	12.31	13.26
8	14.15	14.81	12.70	12.93

Dr. Widtsoe has termed the percentage of moisture held in field soils to a depth of eight to ten feet, with the top foot in a saturated condition, the field water capacity of a soil. In general it has been found that it does not vary very much from the optimum water content for plant growth. For various soils Dr. Widtsoe gives the following values.

Soil to a depth of 8 feet	Field water capacity expressed as a percent by weight	Registered moisture percent by weight on the basis of forty to sixty percent moisture content and thirty percent pore space
Clay	19	16--25
Clay loam	18	9.4--14
Loam	16--17	9--13
Sandy loam	14.5	10--15
Very sandy loam	14	7--10

CHAPTER III

THE CLIMATE

The first factor, influencing the net Duty of water, that will be considered is the Climate under which irrigation takes place.

The annual precipitation and its seasonal distribution, together with the temperature, humidity and wind movements, have a very marked and evident effect upon the amount of water required for crop production, length of irrigation season and the number of irrigations that are applied.

The climate affects not only the total seasonal duty but is also mainly instrumental in determining the actual monthly distribution of the water requirement--a most vital factor to be considered in the design of the distribution system. The monthly requirements are controlled by the crops grown and the locality under consideration. Alfalfa or pasture in any arid region usually requires water throughout the growing season, or from early spring until late autumn, while a grain crop requires water during not more than the first half or two-thirds of the season. Potatoes require water throughout the season, but

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The following two Tables, taken from the report of Don. H. Bark are typical of the irrigated sections of Idaho. The crops and soils were divided into two classes

(1) Grain on medium clay and sandy loam,

(1a) Alfalfa grain on medium clay and sandy loam.

(2) Grain on porous sand and gravelly soil,

(2a) Alfalfa and clover on porous sand and gravelly soil.

TABLE VII

Summary of Depths of Water Applied by Months to 122 Fields of Grain on medium clay and sandy soils (12)

Season	No. of plots	April 15-30	May	June	July	Aug.	Sep. 1-15	Sep. 15-30	Total for season
		feet	feet	feet	feet	feet	feet	feet	feet
1910	39	.00	.320	.645	.495	.095	.00	.00	1.556
1911	49	.00	.021	.717	.428	.006	.00	.00	1.172
1912	34	.00	.000	.914	.650	.059	.00	.00	1.623
Average		.00	.114	.759	.524	.053	.00	.00	1.450
Percentage of Total		.00	7.86	52.34	36.14	3.06	.00	.00	100.00

TABLE VIII

Summary of Depths of Water Applied by Months to 46 Fields of Alfalfa on Medium Clay and Sandy Loam (12)

Season	No. of plots	April 1-15	April 16-30	May	June	July	Aug.	Sep. 1-15	Sep. 16-30	Total
1910	17	.053	.018	.531	.720	.002	.551	.004	.000	2.54
1911	18	.00	.025	.525	.308	.945	.750	.199	.031	2.783
1912	11	.00	.000	.508	.443	.697	.474	.038	.000	2.100
Average		.018	.014	.521	.490	.748	.592	.100	.010	2.50
Percentage of Total		.72	.56	20.90	19.05	30.00	23.75	4.02	.40	100.00

Irrigation water is usually applied during that part of the year which corresponds in general with the period of plant growth. The time to start irrigation is largely dependent on the initial amount of moisture present in the soil--due either to winter rainfall or fall irrigation, the available water supply and the crops to be grown. Soils which have a good water retentive power and which have been subjected to either fall irrigation or winter precipi-

tation, will generally be found to have sufficient initial water in the soil to start plant growth. This is due to the fact, as already shown, that the water may be stored in soils to a considerable depth as a film surrounding the soil particles. At Utah, where most of the precipitation comes in winter, it was found that in the spring most of the water that fell during the preceding winter was held in the upper eight feet (See Table VI). The quantity held in the soil varied with the percentage of water in the soil in the autumn. If the soil went into the winter in a dry condition, practically all of the winter precipitation was found in the spring in the upper eight feet. If, on the other hand, the soil was well filled with water in the fall, a relatively small quantity of the winter precipitation was found in the upper eight feet of soil. The upper couple of feet were, in both instances, fully saturated, and the percentage diminished steadily with increasing depth. Hence it is clear that when the soil was fairly completely saturated in the fall, the winter precipitation passed down beyond the eight feet limit or the root depth. From 1902 to 1907 the percentage of winter precipitation found stored in the soils in the spring--the soil going into the winter in a dry condition --varied from sixty-three to ninety-eight percent. It is

evident therefore that in districts where the precipitation comes in winter, early spring irrigation may have but little value. On the other hand, where the winters are dry and the summers wet, early spring irrigation should prove very profitable.

Porous, coarse, sandy or gravelly soils, which have but little retentive power, will require early irrigation and for new crops may even require irrigation before planting.

The effect that the rainfall, which falls during plant growth, will have depends largely on the amount of precipitation and the relative humidity of the district. It has for instance been shown in Idaho, "that a light summer rainfall has but very little influence on the Duty of water, most of it being evaporated. Heavy rains of .5 of an inch or more at a time seem to have beneficial effects, but the Idaho atmosphere during summer is so dry and the soil is so warm that lighter rains than this seem to do more harm than good, for they not only evaporate before they have had time to penetrate into the root zone, but effectually destroy any soil mulch that may have been formed by cultivation."

The beginning of the irrigation season, may in some cases, also be considerably affected by the temperature

of the water. Cold water, if applied in large quantities, will lower the temperature of the soil below that which is best for plant growth. Hence if the soil has sufficient water for plants to thrive on, it will be detrimental for plant growth to apply irrigation water of a temperature below that of the optimum soil temperature.

CHAPTER IV

MOISTURE DISTRIBUTION IN THE SOIL

It will be well, before discussing the question of the distribution of the moisture throughout the soil, to take up the question of moisture movement.

The moisture in the soil is subjected to various forces of which the following are the most active.

(1) Gravity.................G.
(2) Capillarity.............C.
(3) Film Forces, such as
molecular attraction,
surface tension, etc...F.

In an air dried soil there is a condition of equilibrium. The moisture contained has distributed itself according to the forces acting on it, in this case being primarily film forces. If the hygroscopicity of the soil is satisfied, the moisture acting under capillarity and film forces will distribute itself uniformly throughout the mass. If now this state of equilibrium is disturbed, as by the addition of water or by evaporation from the top soil, the soil moisture will tend to redistribute itself to the new conditions--bringing about thereby a movement in the soil moisture. Moisture will always move from the wetter to the drier soil or from the thicker to the thinner

film--the affinity between soil particle and moisture being so much greater in the latter case. And once contact by this means has been established, it is surface tension that drags or pulls the other particles along.

If the moisture content is somewhere near the lento capillary point, the movement and the distribution will be primarily due to F,G and C. When the maximum retaining capacity of the soil has been reached any further addition of moisture simply slides off the already present moisture film,--neither capillarity nor film action having any hold on the water, gravity alone acting.

The lateral movement of moisture is dependent not so much on the result of capillarity, film action and gravity, but to a greater extent on the first two only. The result, as will naturally follow, is less than in the case of downward movement. Gravity will rather tend to spread the laterally moving water downward in a fan-like formation, giving thus a uniform distribution only below the topmost surface.

The upward movement of the moisture is entirely identical to the downward movement, except that in this case the action is against gravity, whilst in the former case it is aided by gravity. As the particles in the top

surface dry out as by evaporation, there will be a gradual readjustment of the moisture particles from the thicker to the thinner films. But as evaporation is a continuous action, so too will be the movement of the soil moisture from the bottom towards the top, until the loss of moisture will be felt throughout the entire soil mass.

The problem that the irrigation engineer faces, is to be able to tell to what extent this moisture movement will take place in various types of soil or what the distribution through the mass will be. It is essential for him to know these matters, since whilst for one type of soil the water applied will wet the mass throughout the root zone, on another soil the larger portion may be lost by deep percolation, the film action and capillarity being too small to store the water. It is evident that the degree of success which the individual irrigator attains is directly proportional to his ability to grow satisfactory crops by using reasonable quantities of water.

Irrigation water which passes below the root zone of ordinary crops carries with it in solution valuable plant foods, thus tending to ultimately render the soil infertile, or, as often happens, if the downward leaching is checked by an impervious strata, a water-logged condition results, fa-

vouring the rapid accumulation of alkali and hastening, to a marked degree, the non-productiveness of the soil, and thereby the failure of the irrigator. Consequently the importance of gathering information concerning the depth to which soils may be wetted by irrigation cannot be overestimated.

The extent to which moisture will distribute itself after irrigation is dependent on the frictional resistance which the water has to overcome. As soon as the frictional resistance of the soil particles to the moisture becomes greater than the forces bringing about the moisture movement, the distribution will decrease rapidly and further penetration into the soil stopped. The cause of the frictional resistance becoming greater than the movement forces, must be sought in the theory that the water is gradually used up in the form of films in its downward movement. The finer the texture of the soil, the greater will be the aggregate surface exposed by the soil particles and the greater therefore will be the moisture distribution. If, therefore, a definite quantity of water is applied, it will be used up to a much larger extent in the topmost layers by the finer grained soils. A point will hence be reached where there is no longer a sufficient supply of moisture to satis-

fy the wants of film action, frictional resistance will increase rapidly and the distribution of the moisture diminish abruptly

Table IX shows the result of a laboratory experiment on sandy loam. In a glass jar some one and one-half inches in diameter a celluloid lining was tightly placed. The whole was filled with sandy loam, and sufficient water was added to give an irrigation equivalent to one and one-half inches of water in depth. The jar was then covered with a paper to prevent evaporation. At the end of a week the soil column was taken out of the cylinder and unrolled. Samples were taken at the various depths indicated, oven dried, and the amount of water present at each given depth, calculated. Table IX shows the results obtained.

TABLE IX

Depth from surface in inches	Percent water present	Hyg. coefficient	Net capillary water
1	14.35	2.04	12.31
2	12.97	2.04	10.93
3	14.13	2.04	12.09
4	13.63	2.04	11.59
5	15.03	2.04	14.99
6	13.22	2.04	11.18
7	11.88	2.04	9.84
8	9.04	2.04	7.60

The results show a very uniform moisture distribution in the part of the curve AB, and the abrupt decline of penetration after the point b has been passed. Similar experiments conducted through a longer period show that with an increase in time the moisture distribution followed roughly in the way indicated, always converging towards the point c.

These conditions are not necessarily met with in field practice, the part bc of the curve having been forced down to a much greater depth by either the rainfall or ex-

cessive irrigation. But it is abundantly clear that the distribution when the soil is in an air dry condition stops at a very marked depth, where the frictional resistance becomes greater than the forces tending to distribute the moisture. Greater attention should be paid to lighter irrigations so that the total distribution abcd may be kept within the root zone, rather than forcing it beyond that depth by excessive applications of irrigation water.

The frictional resistance will be a large extent be dependent upon the initial amount of water present. The greater this amount, the smaller will be the frictional resistance and the greater will be the downward penetration, and the abrupt change in moisture distribution. It is a matter of common experience, the farmer finding that the water does not penetrate the soil deeply during the first year of irrigation; but, as time goes on, the soil becomes wetter to greater depths, and at the same time less water is required by his crops.

The moisture content of the native undisturbed soil in arid regions is usually below the point of lento capillarity. The first water added is used to bring the moisture content up to this point, and as this is accomplished, water moves downward freely; the plants being enabled to secure their water supply with a corresponding

smaller expenditure of energy. At the Experimental Farm at Davis the results obtained are given in Table X.

TABLE X

Depth	.5	1.5	2.5	3.5	4.5	5.5	Dry at
Percent Moisture on ovendried basis							
Boring I	21.05	18.16	15.33	17.04	20.48	14.29	6 ft.
Boring II	20.49	20.39	19.06	19.04	23.19	14.74	5.9 ft.
Boring III	20.55	17.92	16.04	18.19	13.26	12.55	6.4 ft.

These results were obtained under typical field practice conditions, the samples being taken in an orchard.

The results closely follow those obtained in the laboratory. Is there then for every soil a definite quantity of water which will distribute its moisture uniformly throughout the soil mass to just a sufficient degree and depth to prevent any deep percolation loss and be of maximum use to the plant? It is still too early in these investigations, which are being carried on at present, to arrive at any definite conclusions. One fact is however apparent, that whilst we may increase the duty of water very considerably from purely scientific considerations, it is more the mechanical application of the water in field practice which retards the obtaining of any such increased efficiency of the water. The tremendous waste, due to the improper levelling of the land, the loss at the head of the border or check, the waste at the end of that border or check, the skill of the irrigator and so many other mechanical factors are the more responsible elements for the low duty realized. Even if it were possible to apply water in such quantities as would be best from the preceding considerations, it will always be the mechanical factors to

which prime attention will have to be given for obtaining an increased duty of the available water supply.

The California Branch of Irrigation Investigations of the United States Department of Agriculture has, in co-operation with the State Engineering Department and the Agricultural Experimental Station at Davis, studied during the past three years the distribution of irrigation water in various soils. Observations of the results, which may be regarded as those of typical irrigated soils, will be presented. The observations were made under two somewhat distinct conditions. First, studies were made upon various farms in the Sacramento River Valley, on fields producing alfalfa (lucerne). Soil types representative (according to the Bureau of Soils U. S. D. A.) of extensive areas in the valley, were chosen. The other conditions are those at the University Farm at Davis, where alfalfa was grown upon one-fourth acre square lots. The surface two feet of soil is a loam of remarkable uniformity, and the third to eighth foot sections consist of a sandy loam of recent origin, pocketed at irregular intervals with coarse sand or clay loam. This fine sandy loam lies upon an undulating clay which extends from nine feet to a depth of twenty or more feet below the surface.

Sacramento Valley Experiments

Silt Loam Soils. In Table Xi and Figure V are presented results of moisture determinations upon three tracts, classed as silt loam soils, which are based upon one hundred thirty-eight six feet and thirty-six nine feet borings. The curves of the silt loam soils converge gradually from the surface of the soil downward. This may be due to a large extent to the fact that these soils do not dry out as rapidly at great depths as to the more porous sandy loam soils. The average amount of water held after irrigation was 3.20 inches per foot, or enough to fill fifty-one percent of the pore space.

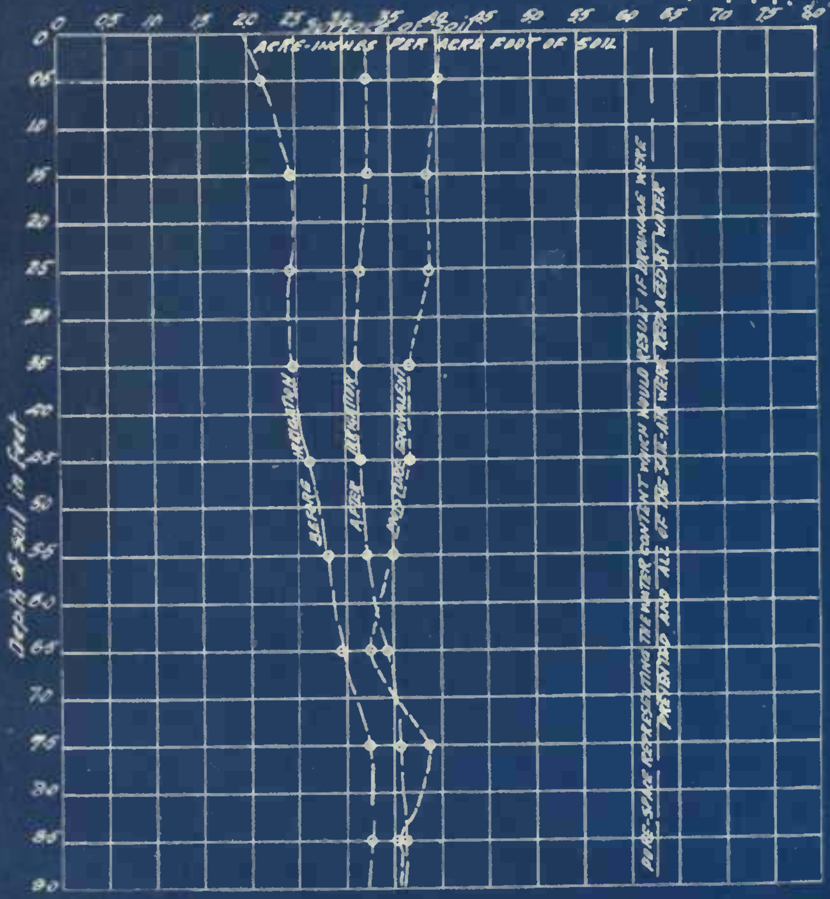

Diagram illustrating soil moisture distribution in a silt loam soil (Israelsen)

FIG V

TABLE XI
SILT LOAM(17)

Tract treatment and time of Samples	No. of samples	Moisture Content in Acre Inch per Acre Foot of Soil									Total water at depth
Depth at which samples were taken											
Bundy, Los Molinos											
Before Irrigation	24	2.54	2.86	2.84	2.84	2.97	3.12	3.19	3.50	3.50	27.56
After Irrigation	24	3.50	3.62	3.01	3.52	3.42	3.53	3.57	3.82	3.90	32.49
Increase		.96	.76	.77	.68	.45	.41	.38	.32	.40	4.83
Hofhenke, Los Molinos											
Before Irrigation	45	2.12	2.43	2.37	2.37	2.44	2.49	2.72	2.99	3.04	22.97
After Irrigation	45	3.27	3.29	3.04	3.00	3.04	3.09	3.26	3.30	3.35	28.64
Increase		1.15	.86	.67	.63	.60	.60	.54	.31	.31	5.67
Averages											
Before Irrigation	69	2.34	2.64	2.60	2.60	2.70	2.82	2.94	3.16	3.27	25.07
After Irrigation	69	3.38	3.45	3.32	3.26	3.23	3.31	3.42	3.56	3.62	30.55
Increase		1.04	.81	.72	.66	.53	.49	.48	.40	.35	5.48

In the case of the Bundy tract, four irrigations were given of 17.22, 12.20, 11.55 and 7.77 acre inches per acre respectively. The moisture determinations indicating that the following amounts were retained in the upper six feet.(18)

Irrigation in Acre inches per acre	Percent acre inches per acre retained on top 6 feet	Percent retained	Percent lost
17.22	4.01	23	77
12.20	3.27	27	73
11.55	4.03	35	65
7.77	4.73	61	39

The Table shows that in this case for a total depth of nine feet only 5.13 acre inches per acre was retained or 44.4 percent of the total, 55.6 percent being lost beyond the root zone. In the Hofhenke tract, the following additional results were obtained.(18)

Acre inches applied per acre per irrigation	Acre inches per acre retained in the upper 6 feet	Percent retained	Percent lost
18.76	5.42	29	71
15.74	3.78	24	76
18.86	5.36	28	72
13.22	3.50	26	74

The results show the obvious fact that the quantities applied were much too great, the losses by deep percolation being in all cases excessive.

TABLE XII

CLAY LOAM SOILS (17)

Tract, location and time of sampling	No. of samples	Moisture Content in Acre Inches per Acre Foot of Soil						Total
Depth at which samples were taken	ft.	.5	1.5	2.5	3.5	4.5	5.5	
O'Hair, Orland								
Before Irrigation	27	1.46	1.83	2.07	2.69	3.21	3.51	14.77
After Irrigation	27	3.14	2.51	2.40	2.71	3.21	3.44	17.41
Increase		1.68	.68	.33	.03	.00	.07	2.64
Geer, Los Molinos								
Before Irrigation	48	2.60	3.06	2.40	2.44	2.06	2.67	15.83
After Irrigation	48	3.67	3.86	3.07	3.17	3.27	3.21	20.25
Increase		1.07	.80	.67	.73	.61	.54	4.42
Guile, Woodland								
Before Irrigation	12	2.23	2.46	2.60	2.67	2.74	2.72	15.42
After Irrigation	12	4.00	3.34	3.18	3.22	3.20	3.18	19.12
Increase		1.77	.88	.58	.55	.46	.46	3.50
Averages								
Before Irrigation	87	2.10	2.45	2.36	2.60	2.87	2.97	15.35
	87	3.60	3.23	2.88	3.00	3.20	3.28	19.19
		1.50	.78	.52	.40	.33	.31	3.84

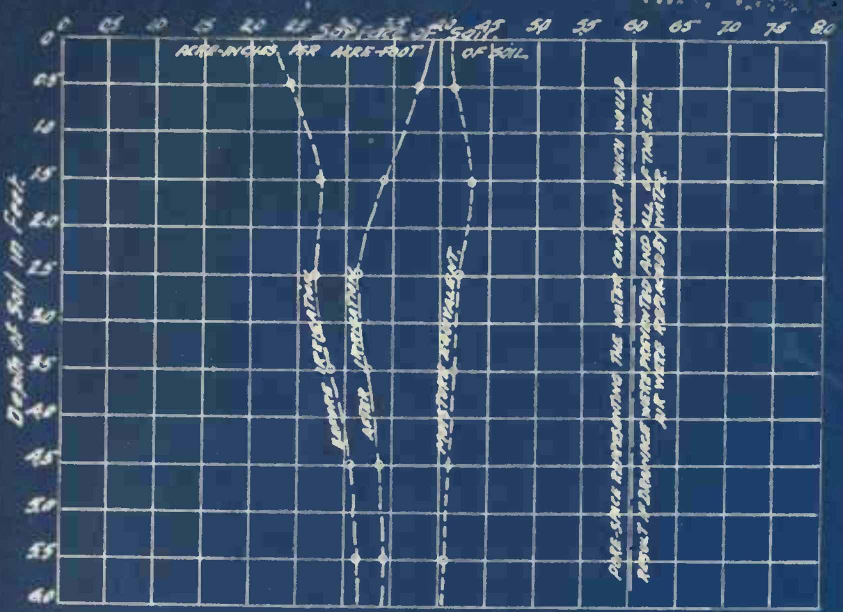

Diagram illustrating the soil moisture distribution in a clay loam soil. (Israelsen)

FIG VI

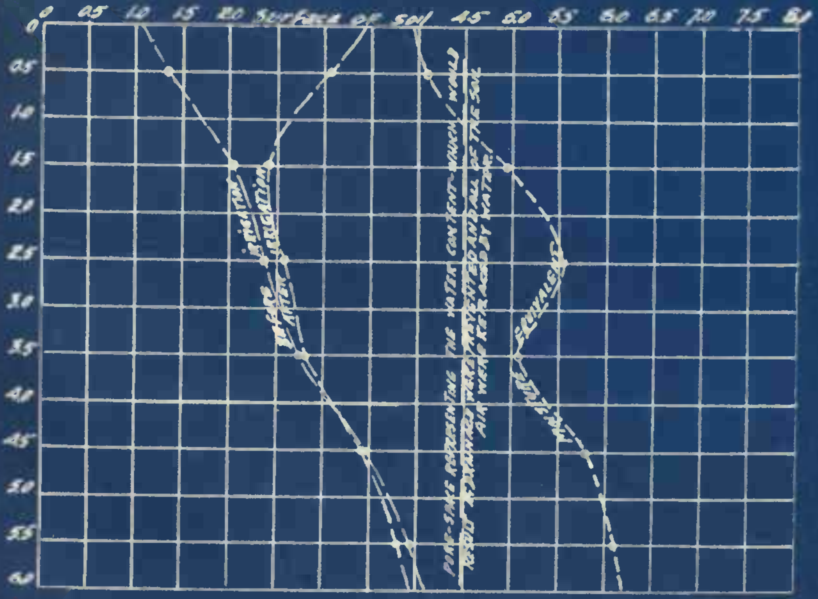

Diagram illustrating the soil moisture distribution in a clay soil. (Israelsen)

FIG VII

Clay Loam Soils

In Table XII and Figure VI are given the quantities of water held before and after irrigation on a number of farms having typical clay loam soils as determined by two hundred ninety-six six feet borings. The Figure represents the average results. The increase in moisture varies from 1.35 in the surface to .28 in the sixth foot, as compared to a variation of 1.13 to .44 in the silt loam soils. The increase in convergence of curves with depth as the texture of the soil increases in fineness is apparent. The water content decreases appreciably after irrigation with the depth of the soil. It is therefore doubtful if the maximum capillary capacities of these soils were satisfied. The average amount of water held by the clay loams after irrigation was 3.49 inches per foot or enough to fill fifty-eight percent of the pore space as compared to fifty-one percent in the case of the silt loam.

The following additional results are given to this type of soils.(18)

Farm	Irrigation in acre inches per acre	Acre inches per acre retained in top 6 feet	Percent retained	Percent Lost
O'Hair	6.24	3.58	57.	43
	3.18	2.11	66.	34
	3.24	2.14	66.	34
Guile	7.28	4.03	55.	45
	5.94	5.41	91.	9
Geer	24.00	5.59	23.	77
	18.19	3.28	18.	82
	12.15	5.37	44.	36
	24.34	3.76	15.	85

A striking condition was obtained in the case of the O'Hair field in that, while the percentage of the irrigation water applied retained in the soil decreased with the depth, the amount of moisture in the soil before irrigations actually increased with the depth, apparently due to the capillary use of ground water, which stood seven to nine feet below the surface.

In the case of the Guile field, very little water penetrated below the sixth foot. At the time of the first cutting the moisture content of the soil was so low, that

nowhere in the upper six feet was it much, if any, above the wilting point. The same conditions were approximated at subsequent irrigations. This no doubt accounts for the large percentage retained, showing again the influence of the initial amount of water present. The smaller the amount of initial moisture present the greater will be the amount retained and kept uniformly distributed. On the other hand the greater the amount of initial moisture present the greater will be the downward penetration of any subsequent additions of water.

Another very striking result from the above Table is the large amount lost beyond the root zone (assumed to be six feet deep) in the case of the Geer tract. This is unquestionably due to the large amount of water used, which should not be mistaken for a large head of water. It is but logical, that once sufficient water has been applied to satisfy the capillary capacity of the soils, any further addition of water will increase that amount which penetrates past the sixth foot in depth, decreasing thereby the percentage retained.

TABLE XIII

CLAY SOILS (17)

Tract, location and time of sampling	No. of samples	Moisture Content in Acre Inch per Acre Foot of Soil						Total
Depth at which samples were taken	ft.	.5	1.5	2.5	3.5	4.5	5.5	0-6 ft
Purdy, Willows								
Before Irrigation	24	1.30	1.99	2.39	2.82	3.71	4.36	16.57
After Irrigation	24	3.03	2.12	2.51	2.79	3.54	4.06	18.05
Increase		1.73	.13	.12	.03	.17	.30	1.48
Tuttle Willows								
Before Irrigation	19	1.40	2.09	2.36	2.64	3.46	3.48	15.13
After Irrigation	19	3.09	2.70	2.65	2.81	3.29	3.52	18.06
Increase		1.69	.61	.29	.17	.13	.04	2.93
Averages								
Before Irrigation	43	1.35	2.04	2.38	2.73	3.44	3.92	15.86
After Irrigation	43	3.06	2.41	2.58	2.80	3.42	3.79	18.06
Increase		1.71	.37	.20	.07	.02	.13	2.20

Clay Soils

In clay soils the maximum water holding capacity is sometimes limited by the pore space. This condition seems to apply to the soils described below, the volume weights of which were found to be very high. The total external surface area of these soils is in all probability very high, to judge from their mechanical analysis, which showed 24.54 percent of total sand, 40 percent silt and 34.84 percent clay. Yet the quantities of water found in them both before and after irrigation were extremely low.

The observations made upon Clay soils are presented in Table XIII and Figure VII. Figure VII is based upon 86 six feet borings and Figure VII contains the averages of 568 borings. The Table reveals at a glance the striking fact that the surface foot of soil was appreciably moistened by the irrigation water. It is doubtful if the capillary capacity of the wetter section was entirely satisfied; yet it held after irrigation 3.06 inches of water or enough to fill 64.3 percent of its pore space. The sixth foot, which was kept moist by the ground water table, contained no gravity water, but eight-six percent of its pore space was occupied by capillary water, leaving only sixteen percent of pore space.

The Purdy field was irrigated four times in the

season. Of the 7.08 inches in depth applied in the first irrigation about twelve percent entered and was retained in the upper three feet of soil, of which about eleven percent was in the upper foot. In other words, practically no moisture penetrated below twelve inches. In the second irrigation a depth of 4.56 inches was applied, nearly all of which penetrated the soil and of which about forty-five percent remained in the upper foot. In the third irrigation a depth of 4.80 inches was applied, of which approximately one-third remained in the upper foot, with no increase below the second foot. The moisture determinations before and after the fourth and last irrigation, when a depth of 3.84 inches was applied, indicated that the soil became more impervious to water as the season advanced, for about sixty-six percent of the amount applied was retained in the first foot, with no significant increase below that.

The soil of the Tuttle field is similar to that of the Purdy field, but slightly coarser in texture and a little more open and permeable. Moisture determinations were made from ten borings before and after irrigation the second irrigation and nine before and after the third irrigation, a depth of 4.08 inches being applied in the first case and 4.16 inches in the second and third irrigation. At

the second irrigation ninety-three percent of the water applied was found to enter the first three feet of soil, about one-half being retained in the first foot. In the third irrigation forty-four percent was retained in the first six feet, three-fourths of which remained in the first foot.

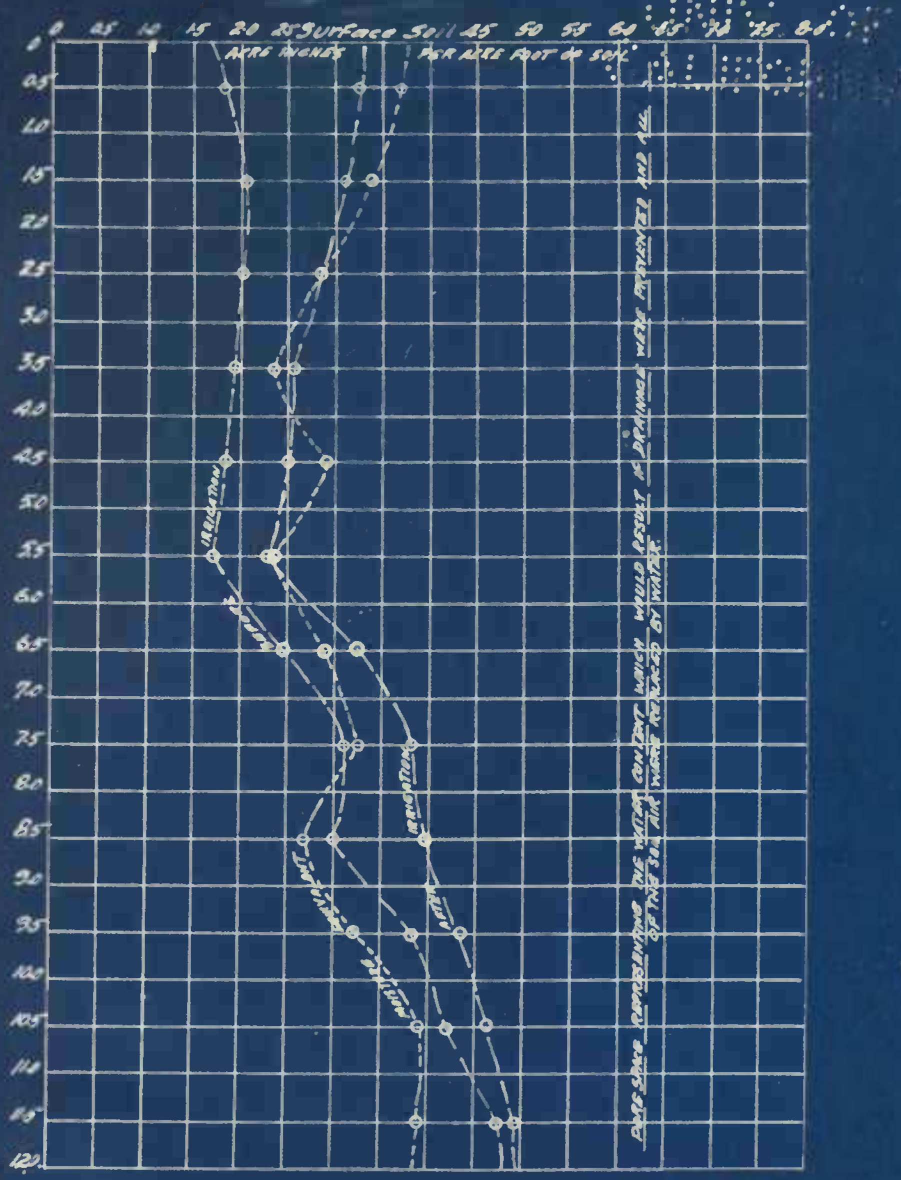

Diagram illustrating soil moisture distribution at Davis, California. (Israelsen)

FIG VIII

TABLE XIV

Irrigation Treatment	Time of Sampling	No. of samples	Moisture content in acre					
Depth at which samples were taken		feet	.5	1.5	2.5	3.5	4.5	5.5
2--6 inches Plot B	Before Irrigation	14	1.78	2.03	2.14	2.46	2.37	2.13
	After Irrigation	14	3.26	2.99	2.86	2.69	2.73	2.19
	Increase		1.48	.96	.72	.23	.36	.06
3--6 inches Plot C	Before Irrigation	21	1.68	1.93	1.91	1.80	1.43	1.29
	After Irrigation	21	3.34	2.99	2.82	2.45	2.10	1.86
	Increase		1.66	1.06	.91	.65	.67	.57
4--6 inches Plot D	Before Irrigation	28	1.76	2.06	2.06	1.87	1.59	1.49
	After Irrigation	28	3.30	3.06	2.75	2.26	2.02	1.87
	Increase		1.54	1.00	.69	.39	.43	.38
4-7-5inches Plot E	Before Irrigation	28	1.95	2.16	2.08	1.85	1.73	1.63
	After Irrigation	28	3.20	3.16	2.95	2.60	2.40	2.19
	Increase		1.25	1.00	.87	.75	.67	.56
4--9 inches Plot F	Before Irrigation	28	1.85	2.04	1.92	1.76	1.87	1.59
	After Irrigation	28	3.17	3.10	2.82	2.52	2.57	2.34
	Increase		1.32	1.06	.90	.76	.70	.75
4-12 inches Plot G	Before Irrigation	28	1.91	2.18	2.05	1.96	2.11	2.32
	After Irrigation	28	3.24	3.30	3.04	2.99	3.23	3.41
	Increase		1.33	1.12	.99	1.03	1.12	1.09
Averages	Before Irrigation	147	1.82	2.07	2.02	1.95	1.85	1.74
	After Irrigation	147	3.25	3.10	2.87	2.58	2.51	2.31
	Increase		1.43	1.03	.85	.63	.66	.57

nches per acre Foot of Soil						Total Water at Depth of		Total percentage of water retained
6.5	7.5	8.5	9.5	10.5	11.5	0-6ft	0-12ft	
						12.91		
						16.72		
						3.81		31.7
						10.04		
						15.56		
						5.52		30.7
						10.83		
						15.26		
						4.43		18.4
1.47	2.81	3.24	3.63	4.25	5.10	11.40	31.93	
2.21	3.64	4.18	4.22	4.52	4.66	16.50	39.93	
.74	.83	.94	.59	.27	.44	5.10	8.00	26.7
2.56	3.38	2.84	4.04	4.53	4.69	11.03	33.07	
3.33	4.08	3.98	4.49	5.08	5.15	16.52	42.63	
.77	.70	1.14	.45	.55	.46	5.49	9.56	26.6
3.37	3.16	2.94	3.88	3.86	4.46	12.53	34.20	
4.22	3.77	3.76	4.32	4.32	4.92	19.21	44.52	
.85	.61	.82	.44	.46	.46	6.68	10.32	21.5
2.47	3.12	3.01	3.85	4.21	4.75	11.46	32.86	
3.26	3.83	3.97	4.34	4.64	4.91	16.63	41.58	
.79	.71	.97	.49	.43	.16	5.17	8.72	

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The amounts of water held at each foot of soil before and after irrigation and the average increase which were found for the various applications are set forth in Table XIV and Figure VIII. The soil of plot B being finer in texture than that of plot D, especially below three feet, accounts for the higher water content both before and after irrigation. (18) Variation in the soil of plot B is probably the cause of an apparent discrepancy in the relative amounts of water accounted for. A comparison of plots C and D indicates that plot C became drier before irrigation than did plot D, which accounts for the greater amount of water being retained by plot C since each plot contained about the same quantity after irrigation. In plots E and G the upper six feet were moistened to their full capillary capacity. It is likely that the clay loam stratum of the seventh foot in plot G by retarding the downward movement caused some gravitational water to be held in the fifth and sixth foot sections till the time of sampling. The effect of the large irrigations of plot G is evident in the great difference between the moisture contained, before and after irrigation, in the

third to sixth foot sections. The twelve inch irrigation of plot G caused slightly greater increases than the nine inch application of plot F in the second to seventh foot.

The upper six feet of the water content curve in Figure VIII plotted from the averages in Table XIV are based on 294 borings; the section seven to nine feet is based upon 120 borings and the depth from nine to twelve feet represents averages of 48 borings. Adams summarizes the results obtained as follows: (18)

> "Not counting the experimental plots at Davis and Willows, moisture determinations were made chiefly on 15 fields, of which 13 were of silt loams or clay loams. In the case of all but one of these loam soils, for which one the full capacity of the soil to retain water was not satisfied, the average quantity of irrigation water retained per irrigation in the upper six feet of soil was equivalent to a depth of only 4.31 inches, or only 32.6 percent of the average individual applications, and only .72 acre inch per acre per foot in depth of the soil. Although the roots of the alfalfa penetrate in these soils to a greater depth than six feet, it is plain that a considerable portion of the irrigation water went below the zone of greater root activity and was largely or wholly wasted.
>
> Considering the quantities of irrigation water retained in the upper six feet of soil for all of the field for which soil moisture determinations were made, it is found that the average quantity retained in the lighter and more permeable soils was .92 acre inch per acre for each in depth of soil, whereas the clay soils absorbed an average of only .37 acre inch per each acre foot of soil, or at the rate of only

2¼ acre inches for six acre feet; due to their great imperviousness in their present conditions. In the surface foot, however, the light soils retained an average of 1.04 acre inches per acre foot of soil as compared to 1.71 acre inches per acre foot held by the clay soils, this being in accordance with the well known fact that clay soils, when once thoroughly wetted, will hold much more soil water than soils of coarser or lighter texture.

Averaging the quantities of irrigation water retained by each field for which moisture determinations were made, it is found that the maximum quantities retained per acre foot of soil per irrigation were 1.02 acre inches for the silt loams with fine sandy subsoils, .75 acre inch for the silt loams without fine sandy subsoils, .78 acre inch for the clay loams and .49 acre inch for the clays.

Considering only the moisture determinations from the surface foot of soil of the 15 farms, it is plain that, in the case of the typical silt loam soils of the Sacramento Valley, single applications of irrigation water, exceeding depths of one to one and one-half inches per foot in depth of soil it is necessary to moisten, accomplish no useful purpose. While the typical clay loams and clays of the valley will retain against gravity in their normal growing condition as much as 1½--1 3/4 acre inches of irrigation water per acre foot of soil, over and above the amount normally found in such soils under Sacramento Valley field conditions, that amount of irrigation water will not be absorbed by these soils unless it is applied very slowly.

The wilting percentages for the Sacramento Valley soils under investigation ranges from 10.35 in the case of the silt loams of the experimental irrigation tract on the University Farm at Davis, to 16.59 in the case of clay loam on the same tract. The average wil-

ting percentages for the several types of soil under observation were 10.65 for the silt loams with fine sandy subsoils, 13.12 for the other silt loams, 14.21 for the clay loams and 13.06 for the clays. The approximate quantities of water necessary to apply to thoroughly dry soils of the types listed to bring the moisture content up to the wilting points given are in inches in depth per foot of soil, 1.5 for the silt loams with fine sandy subsoils, 2 for other silt loams, 2.3 for the clay loams and 2.6 for the clay. The optimum percentage of available soil moisture for Sacramento Valley alfalfa soils over and above the percentage at which wilting occurs, seems to average between 4 and 6%. This is equivalent to depths of from .6 to .9 inch of irrigation water per foot of soil for loam soils and of from .7 to 1.2 inches per foot of soil for the heavier clay loams and clays.

Alfalfa planted on very open and very impervious soils should be irrigated more than once between cuttings. This is necessary in the case of the open soils because of the inability of such soils to retain all of the moisture needed to mature a crop, and in the case of the impervious clay soils in order to accomplish deeper penetration of the irrigation water into them. In case of the latter soils it is very desirable that the moisture supplied by winter rains shall be supplemented by irrigation water sufficiently early in the spring to prevent drying out. The frequent use by irrigators on such soils of a soil auger is to be urgently recommended, the investigations having demonstrated that penetration of irrigation water into the clay soils is very much less than irrigation usually realize.

It will be noticed that the curves plotted from the foregoing result do not bear the same character-

istics of an abrupt diminution of soil moisture at a fairly definite depth as the experiments quoted previously did. The explanation of this is to be found in two factors. In the first instance the initial water content, especially at the lower depths, is much higher than in the first case, where practically air dried soil was used. This will have the effect of decreasing appreciably the frictional resistance that the irrigation water has to overcome in its downward penetration, since the initial water distributes itself as films round the soil particles. The water that is added therefore is under a much smaller influence of soil affinity and the other film forces. There is therefore a greater tendency towards the sliding off from the already existing water films. The higher the initial percentage of water present the greater is the amount that will penetrate downward.

In the theoretical diagram, if the initial water percentage is kf, the amount of water that will be distributed uniformly is cde, whilst if the initial percentage is kg, the excess amount of chj--and the resulting curves before and after irrigation will be as shown--the two curves converging with an increase in depth. In view of the results obtained from these experiments and the assumed

theory it follows that it is not the soil moisture which distributes itself according to the root system of the crops, but it is rather the root system of the crops that distributes itself according to the distribution of the soil moisture.

There is a very mistaken fallacy abroad (especially is this the case in alfalfa) that the soil should be wetted to the depth of the roots, and alfalfa being deep rooted, sufficient water should be applied to penetrate to that depth. But since it is a well known fact that the roots rather distribute themselves according to the prevalent moisture, it follows that any excess water specially applied for deeprooted plants, say below the sixth foot, is practically an entire waste. It has been noted by various authorities that on an average the following percentages of the entire root system for alfalfa penetrate to the depths indicated.

1 foot deep	27 percent
2 feet "	43 "
3 " "	12 "
4 " "	10 "
5 " "	7 "
beyond 5 " "	1 "

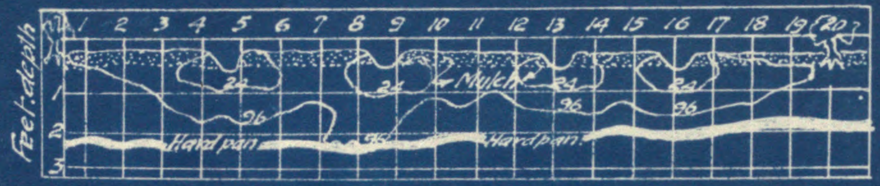


Diagram showing the effect of hardpan on the distribution of furrow irrigation 24 and 96 hours after application.

U.S.D.A. Bul. 203.

FIG. IX a.

CHAPTER V

CHARACTER OF SOIL AND SUBSOILS

Apart from the actual texture and structure of the soil, there are various conditions that are met with which influence the application of water to a very large extent. Foremost of these is the layer of hard consolidated soil particles, known as hardpan. See Fig. IX.

Hardpan is the result, to a large extent, of soil weathering. The finer the particles are broken up, the nearer do they approach that class of soil termed clay. The particles are subjected to percolating water, and the soluble constituents may be taken into solution. Thus we have solutions of sodium carbonate and various silica salts, associated more or less with other products of rock decomposition. It is in the surface soil that these solutions are chiefly formed. And according as their descent into the substrata is unchecked, or is liable to be arrested at any particular level, whether by pre-existing close grained layers or by the cessation of the rainfall, the subsequent penetration of air and evaporation of the water alone by shallow rooted plants, may cause the accumulation of the dissolved matter at a particular

level, year by year. The action is largely accentuated by the filtering action of the minute clay particles which have originally been washed down. The water, charged with these minute particles, precipitates them whilst passing through the accumulated layer already laid down by the percolating water. It therefore is of an accumulative order, the greater the amount of colloidal matter washed down the more extensive will be the filtering action and the thicker will be the resulting hard impervious layer. Once the layer has become impervious the descending water is either used up in transpiration by the plants or by evaporation into the air. The dissolved salts are hence crystallized out and will act as a cementing agent, be it siliceous, calcareous or ferruginous in the consolidation of the accumulated layer. The ultimate result is a hard, consolidated layer known as hardpan.

According to the cementing agent, hardpans will either be an iron, lime or siliceous hardpan. The iron hardpans are exceedingly heavy and much more compact than the lime hardpan. It has the fortunate characterictic that when once broken up by dynamite or some other method, there is but small danger of it reconsolidating. On the other hand lime hardpan, which is readily recognized by its lighter colour and by its rapid disintegration by dilute

acid, may be reformed by the descending water in time to a second hardpan layer. The iron and silica salts, once precipitated out, do not readily redissolve.

It is fairly well established that the lessen the rainfall, the smaller the depth at which hardpan is found and the softer in texture it probably will be. In general, hardpan may be encountered from twelve to twenty-four inches below the surface. If at a greater depth, it will usually be due to the formation of a more recent soil layer on top of the original surface.

It is evident that when such an impermeable layer is allowed to remain near the surface it produces serious results.

(1) By the failure to absorb the greater part of the water, thus permitting it to flow to the lower part of the orchard and out into the adjoining lands, (2) by facilitating sideway surface percolation from the furrows and exposing a greater area to evaporation by the heat of the sun, (3) by holding the water near the surface and thus causing its loss by evaporation before the soil is cultivated, (4) by preventing access of the water to the roots of the trees, if any, lying below the hardpan, (5) by preventing proper ventilation and aeration of the subsoil.

Soils underlaid with hardpan should therefore be irrigated very continuously--a more moderate quantity more frequently applied than for deeper soils being the best practice. It may often be profitable to blast occasional holes through the hardpan to serve as outlets for the excess water that stands on the hardpan. Such blasting, to be effective, should occur frequently, in which case the process becomes highly expensive. Before undertaking this measure, it certainly is advisable to make a thorough examination of the extent of the hardpan, its nature and depth and the type of soil underlying the layer. If underlaid by a heavy substratum like clay, blasting is inadvisable. The extent will not so much be that of opening the soil by cracks and crevices, but rather that of forming a watertight compartment, the clay being compacted all round by the force of the explosion.

The effect of the texture of the subsoil on the use of water is quite material. A heavy soil strata occurring at depths of three to six feet is of much aid both in retaining moisture and in the cross percolation of furrows. The heavy subsoils are in general not entirely impervious to water, the irrigation water penetrating them but the rate at which such water escapes by deep percolation is materially reduced so that the moisture is held for longer periods within reach of

the plant roots. Such a condition is more favourable than an impervious layer like hardpan as in the latter case great care is required to prevent water-logging of the soil.

Where there is no heavy subsoil to assist in causing lateral percolation, the ease with which moisture can pass downward lessens the extent of lateral percolation and a closer spacing of furrows is required to secure an even distribution. A large part of the water applied may also under these circumstances be lost by deep percolation in the upper part of the furrow before the water has reached and irrigated the lower portion.

When the soil is underlaid with gravel, or if gravel seams pass through it within ten feet of the surface, the normal distribution of the soil moisture is disturbed. If gravel is mixed uniformly with the soil from the surface downward, or at varying depths, the soil may be looked upon as being continuous so far as the distribution of water is concerned.

When water, moving downward, reaches a layer of loose gravel, the descent of the moisture film is first arrested, then the film is thickened until the lower soil pores are filled and, if irrigation is continued, gravitational water drips from the soil into the gravel below. The water which thus passes into the gravel cannot move back by capillary means and usually

drains away into the subsoil and is lost to the plant.

Soils, in which such gravel seams occur, should therefore be irrigated lightly. Not enough water should be added to allow any part to move into the subsoil. Under such conditions more frequent applications of water become necessary.

CHAPTER VI

EVAPORATION, PERCOLATION AND SURFACE WASTE LOSSES

The water applied either by precipitation or by irrigation to the land is disposed of in two ways: part of it runs off and is wasted, and part of it soaks into the ground. This latter part is disposed of in three ways (1) by plant transpiration (2) by evaporation and (3) by percolation.

In irrigation it is the object to reduce the surface run-off, evaporation and percolation losses as far as practicable, thereby keeping a maximum amount of the water applied stored in the soil within reach of the roots until such time as it is needed by the plant.

Evaporation. Immediately after the water has been applied to the soil, evaporation begins at the surface and, in time, if not checked, the loss in moisture will be felt throughout the root zone.

The movement of water, as already explained, is from the thicker to the thinner water film or from the wetter to the drier parts of the soil. When therefore the immediate top layers of the soil lose their moisture by evaporation, there is a tendency to partly replace this loss by an upward movement of water from soil particle to soil particle from the wetter subsoil.

As evaporation proceeds from the top soil, the water in every soil layer diminishes to the full depth of the root zone. Dr. Widtsoe likens the action to that of cotton packed loosely in a box. By removing a small quantity, the remainder expands occupying the same volume as before, but in a looser condition.

In soils a similar condition is met, when part of the moisture is extracted, there is a thinner moisture film condition throughout the entire mass. But the degree of drying out is not uniform throughout the soil. It is only in the topmost layers that the process may extend to such a degree that the moisture film is reduced to a minimum for capillary movement. As the lento-capillary point is approached, the upward movement becomes more and more sluggish, and it is very difficult to reduce the lower soil layers below this point even though the upper layers may have a considerably decreased moisture content. To stop this upward movement and thereby the surface evaporation is a chief consideration in irrigation farming where water economy is a vital factor.

The nature of the soil is of considerable importance. The finer the texture of the soil the more rapidly will be the upward movement of the moisture to be changed

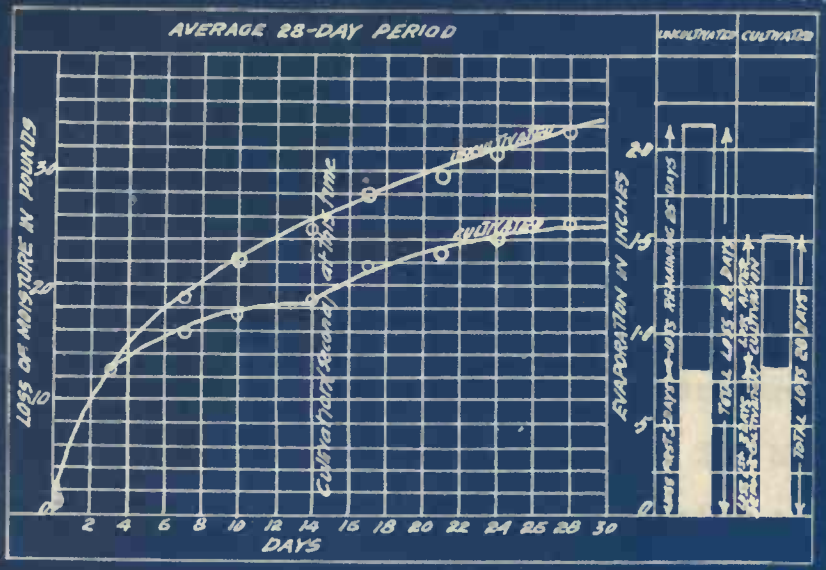


FIG IX

Diagram illustrating the saving obtained by cultivation U.S.D.A. Bul. E

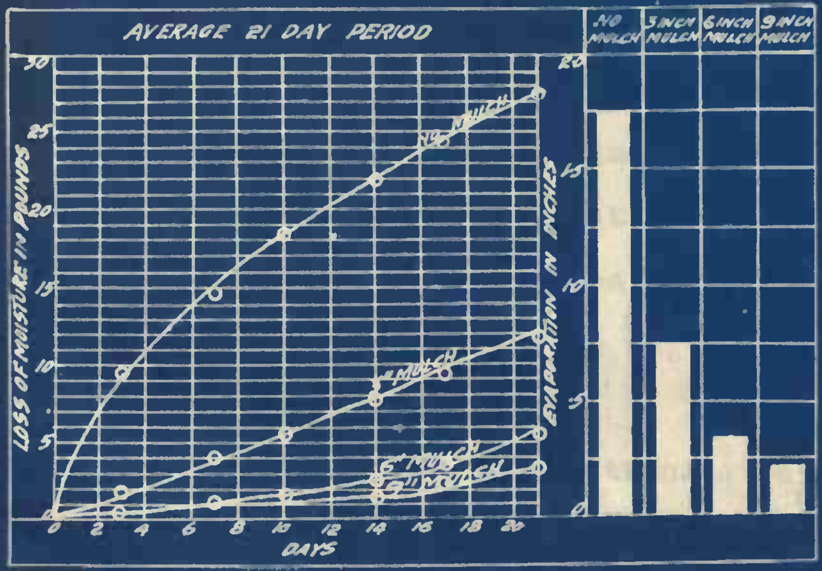


FIG X

Diagram showing the effect of mulches of various depth on the amount of water evaporated.
U.S.D.A. Bul. 2

into vapour. The darker the colour, the more heat it absorbs and hence the greater the evaporation. The richer the soil is in soluble salts, the slower is the evaporation of water into the air.

Of the meteorological factors, the evaporation is most largely influenced by the temperature, sunshine, relative humidity, wind and rainfall. The higher the temperature, the more rapid is the conversion of water into water vapor. Much more water is lost from a wet soil on a sunny day than on a cloudy day. The drier the air, the more rapidly will the air take up water vapour. Winds, likewise, exert a strong drying effect on soils, especially in the case of relatively dry wind. It has also been shown that the wetter the soil is at the surface the more rapidly will be the water evaporated therefrom. The evaporation of water from a soil varies as the initial percentage of the soil moisture.

The results of the observations at six stations at which evaporation experiments were conducted under Dr. Fortier are shown in Tables XVI and XVII. The saving by cultivation is also clearly shown in Figure IX.

TABLE XVI(9)

Period	Days	Mean temp. of air per-cent	Mean humidity per-cent	Mean Vel. of wind per hour miles	Loss from a water surface inches	Cultivated				Uncultivated			
						Tanks 1 and 2		Tanks 3 and 4		Tanks 5 and 6		Tanks 7 and 7	
						Loss	Per-cent	Loss	Per-cent	Loss	Per-cent	Loss	Per-cent
1	3	66.1	40.4	8.5	1.17	12.67	13.5	12.63	13.4	13.23	14.1	12.60	13.4
2	4	62.9	38.8	8.0	1.29	3.31	3.5	2.72	2.9	5.79	6.2	5.81	6.2
3	3	64.7	41.7	9.3	1.18	1.52	1.6	2.06	2.2	3.58	3.8	3.36	3.6
4	4	65.2	51.6	7.9	1.08	1.39	1.5	1.10	1.2	2.25	2.4	2.81	3.0
5	3	66.5	42.7	8.3	1.06	3.24	3.4	2.73	2.9	3.19	3.4	3.12	3.3
6	4	68.7	43.8	9.0	1.33	.67	.7	.93	1.0	1.87	2.0	1.55	1.6
7	3	67.5	42.4	8.2	1.22	1.96	2.1	1.41	1.5	2.17	2.3	1.66	1.8
8	4	68.8	47.0	7.9	1.38	.80	.9	.68	.7	1.73	1.8	2.28	2.4
Average	28	66.3	43.8	8.4									
Total for 28 days					9.71	25.56	27.2	24.26	25.8	33.81	36.0	33.19	35.3
Equivalent of total loss in inches						1.58				2.13			

TABLE XVII(9)

Table showing the losses from free water surface and from cultivated and uncultivated tanks at various stations

Stations	No. of trials	Temperature per-cent	Total rain-fall inches	Free water in soil per-cent	Evaporation from free water surface inches	Loss from cultivated soils inches	Loss from uncultivated soils inches	Saved by cultivation percent
Sunnyside, Wash.	1	65.2	1.00	6.00	7.25	1.47	2.47	40.3
Davis, Calif.	2	64.5	.00	12.85	9.41	1.36	1.91	28.2
Reno, Nev.	2	56.6	.39	8.88	8.49	1.09	1.51	27.8
Caldwell, Ida.	2	72.2	.14	6.21	9.81	1.91	2.42	21.0
Agricultural College, N.Mex.	2	74.5	.57	---	11.13	1.37	1.59	13.8
Bozeman, Mont.	1	64.4	.99	17.80	4.38	2.30	2.92	21.2
Average		66.2	.35	10.35	8.41	1.58	2.14	26.4

The average total losses shown by the above data are 2.13 inches from the uncultivated and 1.58 from the cultivated soils, being 35.5 and 26.3 percent respectively of the total six used in irrigation. The reduction by cultivation amounts therefore to 25.8 percent.

The process is not difficult to understand. Water moving toward the soil surface must pass from particle to particle through the various films at the points of contact of the soil particles. The smaller or the fewer these points of contact, the more difficult will be the upward movement of the water. When the top soil is loosened, the points of contact between the loose soil above and the compacted soil below become reduced, and hence the ascending water finds it difficult to pass through the fewer points of contact. The more thorough the cultivation, or the fewer the points of contact, the more difficult will be the upward movement and the greater will be the reduction in evaporation losses. It therefore follows that the deeper the mulch, a greater saving can be expected. That this is the case is shown by Table XVIII which shows the average losses by evaporation from a free water surface and from tanks with mulches of different depths at five different stations.

TABLE XVIII(9)

Period	Days	Loss from	Loss from Soil			
			No Mulch	3" Mulch	5" Mulch	9" Mulch
		Inches	Pounds	Pounds	Pounds	Pounds
First	3	.86	9.6	1.9	.48	.48
Second	4	.95	5.1	2.1	.56	.56
Third	3	.87	3.7	1.6	.63	.25
Fourth	4	.95	3.6	2.3	.89	.43
Fifth	3	.97	2.3	1.5	1.08	.53
Sixth	4	.99	3.1	2.4	1.73	1.07
Total	21	5.59	27.4	11.8	5.37	3.32
Equivalent loss in inches			1.75	.75	.34	.22

Table XVIII and Figure X show that from an open unmulched soil surface for a period of three weeks the average loss was 27.4 pounds, which is equivalent to 1.75 inches of water. The percentage saved from each depth is shown in Table XIX.

TABLE XIX (9)

Condition of Sod	Evaporation loss		Percent of saving on evaporation from unmulched soil
	Inches	Percent of water applied	
No mulch	1.75	29.2	00--
3" mulch	.75	12.5	57.0
6" mulch	.34	5.7	81.0
9" mulch	.22	3.65	87.5

The saving therefore of a six inch mulch and a nine inch mulch varies but little and it is questionable whether it is economical to go beyond the six inch depth.

In localities where the available water supply is limited and where the duty of water is high, conditions have forced the irrigator to resort to methods of irrigation which will result in a lesser waste of water than that of flooding the entire surface. In orchard irrigation expecially, but also very extensively in all crops that are grown in rows, furrow irrigation has been largely adapted. The present tendency is to use deeper furrows than formerly used. The reason of this practice is not far to seek, in that it is quite evident that under such conditions a smaller percentage of moisture will rise by capillarity to the surface to be evaporated.

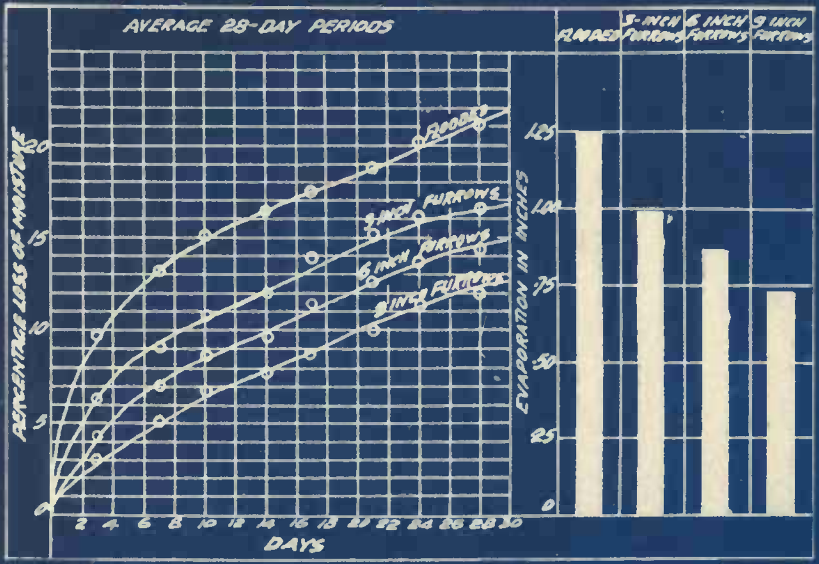


FIG XI

Diagram showing evaporation losses from flooding and with furrows of various depths. U.S.D.A. Bul. 248

Tables XX and XXI give the result of the experiments conducted by Dr. Fortier to determine the saving of water by various depths of furrows. The tanks received a six inch depth of irrigation water, followed by a six inch mulch as soon as the soil could receive it. The results are illustrated in Figure XI.

TABLE XX*(9)*

Period	Days	Loss from water surface inches	Flooding		3" furrows		6" furrows		9" furrows	
			Loss	Per-cent	Loss	Per-cent	Loss	Per-cent	Loss	Per-cent
1	3	1.10	9.14	9.7	5.95	6.3	4.00	4.3	2.85	3.0
2	4	1.50	3.17	3.4	2.57	2.7	2.50	2.7	1.85	2.0
3	3	1.20	1.83	2.0	1.58	1.7	1.43	1.5	1.63	1.7
4	4	1.60	1.15	1.2	1.15	1.2	1.00	1.1	.85	.9
5	3	1.12	1.10	1.2	1.80	1.9	1.68	1.8	1.12	1.2
6	4	1.47	1.12	1.2	1.22	1.3	1.15	1.2	1.08	1.2
7	3	1.07	1.32	1.4	.90	1.0	1.00	1.1	1.22	1.3
8	4	1.40	.82	.9	.45	.5	.68	.7	.70	.7
Total Loss	28	10.46	19.65	21.0	15.62	16.6	13.44	14.4	11.30	12.0
Equivalent loss in inches			1.25		.98		.86		.72	

TABLE XXI (9)

	Loss by evaporation	Amount saved over free water surface		Amount saved over flooded surface		Amount saved over surface irrigated with 3" furrows		Amount saved over surface irrigated 6" furrows	
	Inches	Inches	Per cent	Inches	Per cent	Inches	Per cent	Inches	Per cent
Water surface	10.46	--	--	--	--	--	--	--	--
Flooding	1.25	9.21	88.0	--	--	--	--	--	--
3 Inch furrows	.98	9.48	90.6	.27	21.6	--	--	--	--
6 Inch furrows	.86	9.60	91.8	.39	31.2	.12	12.2	--	--
9 Inch furrows	.72	9.74	93.0	.53	42.4	.26	26.5	.14	16.3

Percolation. Of all the losses in the application of water to the land, deep percolation generally accounts for the greatest portion. As stated before the probable loss by deep percolation is generally from twenty to fifty percent of the water applied.

As shown by Table XIV diagrams of the moisture determinations on the alfalfa experiments at Davis farm, given previously, for the various irrigations fifty-seven, seventy-four, and fifty-four percent of the water applied percolated below the first six feet with an average of 68.8 percent.

Table XXII has been compiled for the various soils on which the alfalfa experiments were conducted, showing the loss by deep percolation.

TABLE XXII

Class of Soil	Average depth applied per irrigation	Quantity retained by upper six feet of sod	Quantity of water retained including probable evaporation losses	Percentage retained including probable evaporation losses	Loss due to deep percolation below six foot limit Percent
Silt loam with sandy loam subsoil	15.02	5.52	6.60	43.9	56.1
Silt loam	12.81	4.24	5.32	41.5	58.5
Clay loam	8.78	3.50	4.56	52.0	48.0
Clay	4.72	2.20	3.28	69.4	30.6
Very heavy Clay	3.67	1.06	2.14	58.3	41.7

As was to be expected the results show that the percolation losses were rather heavier on the lighter silt loam soils than on the clay soils. Percolation may be looked upon as capillary movement of water aided by gravity, and since any capillary movement is dependent on the texture of the soil, so too is the rate of percolation to a large extent proportionate to the texture of the soil. Measurements have been made which show an absorption on blow sand soils

of as much as twelve feet of depth of water in twenty-four hours. On the other hand it has been found that in the case of a well dug in heavy clay in the Sacramento Valley, the water had not yet percolated twelve inches laterally in a week's time. The general rates of percolation to be expected in depth of water in foot per twenty-four hours *(Harding)*

Medium heavy soils	1 foot
Clay loams	2 feet
Loam	3 "
Sandy soils	5 "

With light soils it is difficult to cover the surface sufficiently quickly so that no part will absorb more than can be retained; with heavy soils the difficulty is to secure full absorption of the water to the required depth.

It follows therefore that where for instance for alfalfa on a sandy loam the best practice would require four to seven and one-half inches irrigations (assuming a maximum beneficial seasonal use of thirty inches), it would be best to apply eight to three and three-fourths irrigations in the case of sandy soil and clay soils,--in the first case to prevent deep percolation loss, in the second

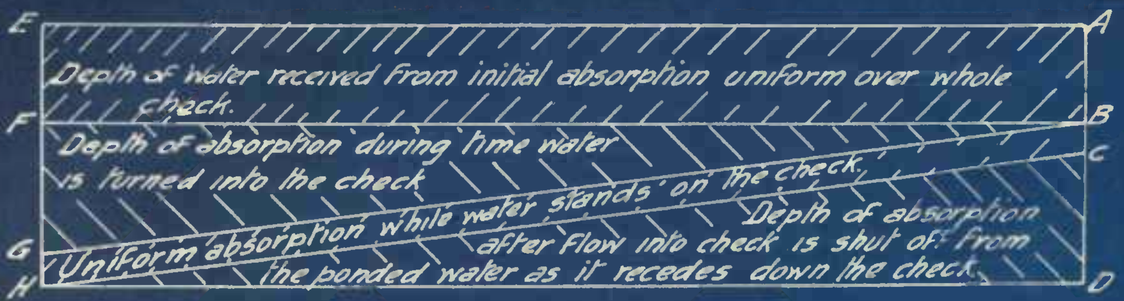


Diagram illustrating the method of absorption of water on sloping checks (Harding)

FIG. XII

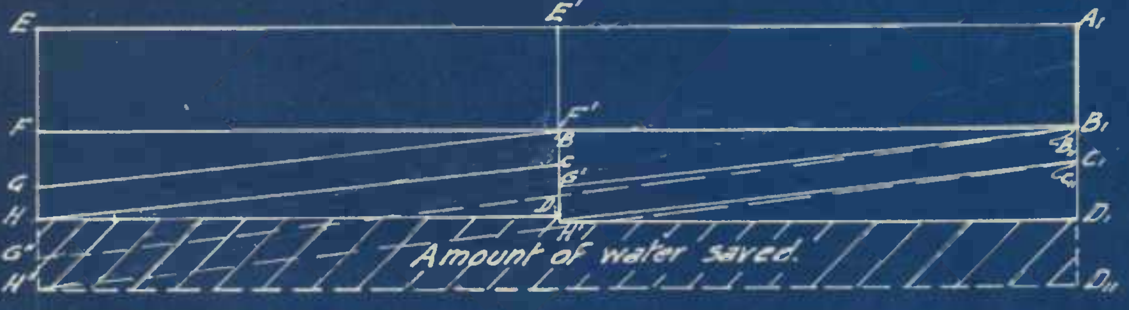


Diagram illustrating the saving in water obtained by using a smaller length of check. Amount saved = shaded area $HH_{11}D_{11}D_1H_1D$.

FIG. XIII

to secure full absorption. The most common method of applying the water to the land is by spreading it over a slightly sloping surface. Under such conditions the distribution of the water should theoretically, be somewhat as shown in Figure XII.

The depth of initial absorption efba represents the minimum depth of irrigation with which the land can be covered under any conditions. As the water travels over the check, the depth of absorption from the flowing stream will be proportional to the time during which each part of the check is covered, being greatest at the upper end, as shown by fgb--gb being somewhat concave upward as the water will travel more rapidly at the upper end. When the water has reached the lower end or often somewhat before it has reached the end, the supply is shut off. For a short period all of the area would be covered and absorption takes place uniformly over the whole check, as shown by chcb. Gradually however the upper end will become unwatered and the water on the check will recede toward the lower end, the absorption being greatest at the lower end where the water remains the longest as represented by hdc. The total depth at the top of the check will hence be eh and will necessarily be a function of the length of the check or ea. If therefore it should oc-

cur that at the head of the check water is lost by deep percolation, this can be considerably diminished by dividing the check into a number of subsections, obtaining a distribution as on Figure XIII. The dotted lines shows the distribution with an undivided check. The saving in water is therefore represented by the area $HH_{''}\ D_{''}\ D_{'}\ H_{'}\ D$.

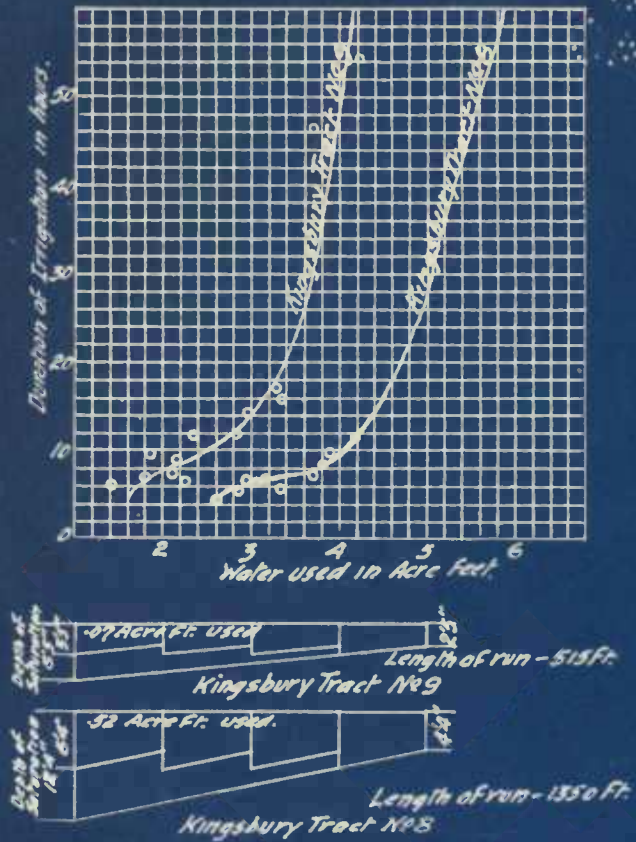
Don. H. Bark has conducted extended experiments illustrating these relations.

An experiment was conducted on a strip of clover 45.9 feet wide and 2359 feet long. The strip was divided into seven equal divisions 337 feet long and a head of approximately three cusecs was turned into the upper end of the strip. The head was held constant and the length of time that was required for the water to advance across each successive division as the stream advanced down the border check was noted. The results in Table XXIII were obtained.

TABLE XXIII (6)

Division number	Length of run feet	Irrigated area acres	Time required		Acre feet Applied	Average depth in feet
			Hours	Minutes		
1	337	.38	1	7	.28	.73
1--2	674	.77	2	30	.63	.82
1--3	1011	1.15	4	00	1.01	.88
1--4	1348	1.53	5	40	1.43	.93
1--5	1685	1.92	8	25	2.12	1.11
1--6	2022	2.30	11	30	2.90	1.26
1--7	2359	2.68	15	40	3.95	1.47

The Table shows clearly that the amount of water that is required for the irrigation of gravelly soils increases greatly with the distance over which the water is flooded. Had this strip been divided into seven sections by the construction of six cross ditches, the time required would have been only seven times as long as that required by the first strip, or only seven hours and forty-nine minutes, as compared to the fifteen hours and forty minutes that were required. Also an average depth of application of only .733 feet would have been required as against the 1.47 feet which were required when it was flooded the



Diagrams showing loss of water by excessive length of run.

Etcheverry

FIG XIV

entire length of the 2359 foot border. A total saving of fifty percent in the time water used would have resulted. The results emphasize the fact that the economical irrigation of especially porous soils can only be effected by flooding comparatively short distances at a time.

The effect of varying the size of head was investigated by the United States Reclamation Service in 1910 and 1911. The curves in Figure XIV show the relation between the number of acre feet on the tract and the duration of the irrigation, which depends on the head of water used.

Table XXIV has been compiled for Kingsbury Tract No. 8, assuming various times in which the irrigation was to take place.

TABLE XXIV(6)

Time	Acre feet of water registered	Corresponding head in cusecs
5	2.60	6.25
8	3.70	5.60
10	4.0	4.8
16	4.5	3.02
20	4.7	2.85
60	5.9	1.17

The results show that decreasing the size of irrigation head, causes a proportionately larger increase in the time necessary to obtain a complete irrigation, and therefore requires a greater depth of irrigation water per acre and a greater loss by deep percolation.

The degree to which these principles have been adopted in practice is shown to some extent by the following. Usually checks vary from three hundred thirty to thirteen hundred twenty feet in length, six hundred sixty being typical for medium soils. The width of the check is adjusted to the soil, slope and size of irrigating head. The widths vary from thirty to one hundred feet for different slopes and sizes of head, the narrower checks being

used on steeper slopes with smaller head. Checks 66 x 660 contain one acre and are typical of the practice under conditions suited to border irrigation. The size of the stream varies from about .02 to .15 cusec per foot width of check or from two to ten cusecs,--the most usual conditions being .08 to .10 cusec per foot width of check. The slopes to which this method is best adapted varies from two inches to one foot per hundred feet, slopes of four to six inches being the most usual.

In furrow irrigation it is difficult to obtain a uniform application throughout the length of the furrow. The best method to obtain a fairly uniform distribution is to either reduce the total length of the furrow, or to increase the length of the furrows in the lower portions of the fields by zigzagging them in orchards or building small basins for ponding purposes. The size of the furrows can be adjusted to the slope and head in each furrow, in light soils using as large furrows and heads as will not cause erosion; on heavy soils, smaller and longer furrows with corresponding longer "sets" should be used.

The lateral percolation in furrows has been extensively studied by Dr. Loughridge. The water applied moves not only vertically downward, but in every direction from the

wetted furrow. The downward movement, aided by gravity, will be the most rapid, diminishing as it becomes more and more horizontal. This is very clearly brought out by the experiments of Dr. Loughridge and McLaughlin, quoted previously.

TABLE XXV(25)

Water removed from tanks by days expressed in percentages of amount in thirty days.

Days	Decomposed light sandy soil 20	Loam 31	Heavy clay loam	Sand and gravel wash 70	Heavy lava ash 90
1	17	22	26	18	17
3	30	36	42	30	29
5	38	42	51	36	37
10	53	58	67	52	53
15	67	70	78	64	67
20	81	81	86	79	81
30	100	100	100	100	100

Table XXV shows the great use of water during the first days of the experiment. In all cases more than one-half the total quantity of water used in thirty days was used in the first ten days or one-third of the time. The

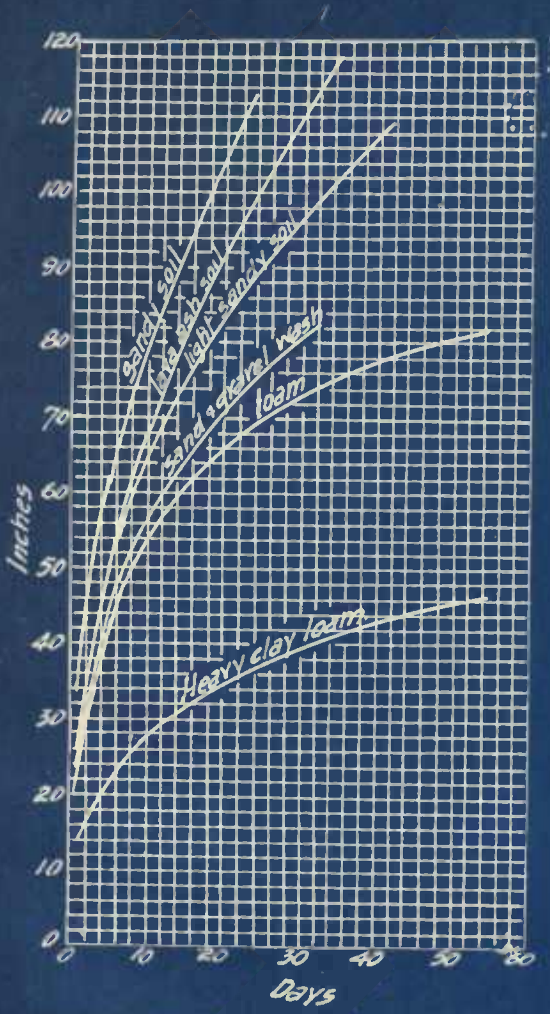


Diagram showing the lateral movement of soil moisture. U.S.D.A. Bul. 835

FIG XV

lighter the soil the smaller the relative percentage of water used during the first days, and the heavier the soil the greater the relative use of water during the first few days.

Figure XV from the experiments of McLaughlin shows that the heavier the soil the less extended will be the wetted area with the lapse of time. Therefore, a light soil will "sub" much farther in a horizontal direction than a heavy soil.

The law of lateral distribution of the moisture is in general of the same nature as for downward movement i. e. the water will tend to distribute itself inversely with the distance of the soil particle from the source of supply.

TABLE XXVI(25)
Distribution of moisture in horizontal flumes

Light sandy soil		Loam		Heavy clay loam		Heavy lava ash	
Distance Inches	Average percent of moisture	District	Average	District	Average	District	Average
3	24.38	9	22.85	3	44.58	5	31.07
9	20.85	22	23.10	12	43.61	9	28.85
21	20.81	34	21.25	34	40.49	18	27.21
45	18.22	52	19.50	30	39.43	30	26.40
69	16.70	64	15.85	33	36.33	42	25.57
81	14.24					54	25.47
93	14.18					72	20.49
105	12.36					84	22.57
111	10.54					96	19.20
117	7.56						

Observations on medium heavy soils in the Sunnyside project indicate that by six days after irrigation the moisture will be relatively uniform across furrow spacings as wide as six feet where water had run in the furrows for twenty-four hours. It was also found that fairly uniform moisture distribution was secured within forty-eight hours after irrigation with twelve hour sets on four feet furrow spacings. With sandy soils without heavy subsoils where the

furrow spacing exceeded three feet heavy downward movements occurred before the moisture met laterally between furrows with heavy subsoils at depths of from four feet. Four feet spacing of furrows gave good results. The trend of practice is in favour of a smaller number of furrows of greater depth, in which small streams of water are permitted to run fifty to seventy hours. This increase in the "sets" has not increased the total quantity applied in any one season for there has been a corresponding decrease in the number of irrigations. This method not only reduces the amount of moisture lost through evaporation by upward capillary movement, but also distributes the water in the subsoil more evenly and produces a greater sideway absorption. It also tends to produce a deeper root system in the crops.

The size of head or the flow turned into each furrow should be adjusted to the soil, slope and length of run --as pointed out previously. The best results are secured by using larger heads until the stream has worked through to near the end of the furrow and then reducing the amount in order to prevent excessive waste.

The size of the stream used in each furrow is most conveniently expressed by giving the number of furrows which would be set with a flow of one cusec. On heavy soils one

hundred to one hundred fifty furrows per cusec are often used. On the heaviest types which absorb water slowly, two hundred furrows per cusec are not unusual and on steep slopes this may reach five hundred in extreme cases. On sandy soil the head used per furrow is generally 1/100 Where the slope is flat larger heads are preferable, 1/60 cusec being an average.

Surface Waste. This loss is largely dependent on the skill and care taken in the preparation of the land for irrigation and in the application of the water. The run-off collects in hollows or cuts channels to connect it with the larger bodies of surface water. When water is applied by the flooding method, it is relatively easy to control the run-off by building levees around the field--as in the Border and Check methods. In such cases the waste should be negligible in amount. Flooding methods will on an average give a ten percent waste and furrow irrigation, due to the greater difficulty in obtaining a uniform distribution, will generally have a somewhat larger waste. In any case, the run-off water should be carefully and skilfully used on lower fields. The problem is one which must be solved on its merits on each individual farm. No general rules can be laid down for using the run-off, as necessarily this use

will depend largely on the layout of the individual farms. Table XXVII shows the average waste from fields at Billings, Montana, for different crops and soils in percent of total water received.

TABLE XXVII

Average waste from fields under different crops at Billings, Montana. (Harding)(21)

Crop	Heavy Soil		Medium Soil		Ligh Soil		All Soils	
	No. of observations	Mean percentage of waste	No. of observations	Mean percentage of waste	No. of observations	Mean percentage of waste	No. of observations	Mean percentage of waste
Alfalfa	56	19	78	4.5	20	5.7	154	10
Grain	15	15	36	5.5	11	14.3	62	9.4
Cultivated Crop	13	20	20	.6	6	9.2	39	8.5
Mean for all	84	18.5	134	4.5	37	9.0	255	9.7

CHAPTER VII

THE FERTILITY OF THE SOIL

It is often taken for granted that irrigated lands do not require any artificial fertilizer because of the fact that the water itself furnishes the required fertility. While a good irrigation system does have great advantages and while the silty waters used in irrigation frequently carry valuable fertilizing material (See Table XXVIII), dependence for maintaining and increasing the fertility of arid lands cannot be placed wholly upon the applied irrigation water.

TABLE XXVIII

Showing the amount of fertilizing silts in various rivers of the U.S.A. (Etcheverry)

River	Pounds of Potash per acre foot of water	Pounds of Phosphoric acid per acre foot of water	Pounds of Nitrogen per acre foot of water
Rio Grande	325.5	31.4	24.4
Salt River	265,	10.5	9
Colorado River	16.34--444.60	2.26--43.56	1.03--69.7

Even in Egypt, where the Nile sediment has a high fertilizing capacity, it has been found that manure and artificial fertilizers should be used. Sir William Willcocks in his "Egyptian Irrigation" says (4)

> "It would be a healthy innovation, indeed, if the provision of suitable manures were to be considered as an essential part of the project for providing perennial irrigation. The day is not distant, I believe, when governments which provide irrigation works will also provide manures, and sell the water and manures together, one being as essential as the other. I know well, from observation, that a well manured field needs only half the water that a poorly manured field does; and in years of drought and scarcity manures almost take the place of irrigation. Why should there not be a manure rate as well as a water rate?"

Organic matter, especially when it has been reduced to the form of humus, has a great capillary capacity, far excelling in this regard the mineral constituents of the soil. Its porosity affords an enormous internal surface, while its colloids exert an affinity for moisture which raises its water capacity to a very high degree. Its tendency to swell on wetting is but a change in condition when approaching its maximum moisture content. The following data, taken from Lyon Fippin and Buckman, give an idea of the capillary capacity of the soil organic matter.

	Percentage of water
Humous extract from peat	1200
Non-acid extract from peat	645
Vegetable mold	309
Peat	190
Garden loam 7% humus	96
Illinois prairie soil	57
Field loam 3.4% humus	52
Mountain Valley loam 1.2% humus	47

Even after allowance has been made for an increased hygroscopic coefficient due to an increase in organic matter, the effect of the latter is very strongly marked on the capillary capacity of a soil. It is equally evident that with a well manured soil there will as a consequence be a marked economy in the amount of water used to procure a reasonable crop.

The experiments at Utah on grain and stover gave the following results--an average of six years.

TABLE XXIX(16)

Irrigation applied	Grain Bushels per Acre				Stover Tons per Acre			
Inches	No manure	5 tons manure	15 Tons manure	Average	No manure	5 tons manure	15 tons manure	Average
None	57.9	73.3	75.9	67.0	2.11	3.25	3.92	3.09
5	61.0	86.1	91.4	79.5	2.32	3.77	4.48	3.53
10	59.7	83.0	92.5	78.4	2.55	3.73	4.25	3.51
20	67.6	87.7	99.1	84.8	2.81	4.04	4.85	3.90
30	63.1	90.4	95.7	83.1	2.86	4.19	4.77	3.94
	63.9	83.8	90.0	79.2	2.88	4.07	4.50	3.81

The results show the highest yield of grain with a twenty inch irrigation duty; more than this quantity of water decreased the yield, and with as much as forty inches of water there was slightly less grain than with five inches. A somewhat higher yield of stover was obtained with thirty inches than with twenty inches of water, but the yield was decreased with forty inches. The average of six years shows that water applied in excess of twenty inches to corn was not only wasted but was postively injurious to the yield of grain. The yield of both grain and stover was decidedly increased by manure, the stover showing the effect considerably more than the grain.

The increase was much greater for each ton of manure with the five ton than with the fifteen ton application.

Most of the soils of the irrigated regions are deficient on humus and organic matter, and it should always be the first object to supply this necessary amount of fertilizer. This is usually done by the growth of alfalfa, clover, peas or some other legume, turning in the green crop and thus putting the nitrogenous matter directly into the ground. It is often desirable and necessary to supplement this by some form of fertilizer, usually the ordinary stable or barnyard manure.

If leguminous, it is generally grown as a cover crop during the non-irrigated months of the year. Much of the success of this method is dependent on the skilfull handling of the water supply. During winter months the cover crop will receive all the necessary water from the rainfall, but great care must be exercised during the summer months that the water intended for the main crops is not absorbed by the cover crop to the detriment of the first. In some localities an extra amount of water is put on the land especially for the cover crop,--being in addition to the required amount of the main crops. In other districts again, it is the practice, to apply only sufficient water for the main crops and to let the cover crops care for themselves. It is

only by experience that one can obtain the best practice --each district having its own individual merits.

The amount of organic matter can be greatly increased by always ploughing in the stubble of the previous crop. On no account should it be burnt. By burning all the nitrogen is taken away by oxidation and only ash left.

A thorough rotation of crops also greatly helps in retaining the amount of organic matter. Experimenting in Oregon Professor W. L. Powers states that "It is probable that the water requirement may be decreased one-third where a good crop rotation is practiced."

CHAPTER VIII

THE CROP

In one of the previous chapters it was stated that under ideal conditions, irrigation should take place when the soil moisture has reached a point somewhat above the wilting coefficient, and that the frequency of application would be dependent on the time taken by the soil to "dry up" after the application of water to the next stage just above the wilting point. This applies, of course, only theoretically. In practice it is necessary to take into consideration, in addition to the above, the effect of such waterings on the crop itself, at the particular period at which the water is applied. It is not so much the case of obtaining, by irrigation, a maximum amount of dry matter per cusec of water applied, but rather a maximum yield of the useful part of the crop. It is hence of importance to know in what way the general growth of the plant is affected by a variable application of water.

Assimilation and other processes favouring plant growth are especially rapid after an irrigation, gradually diminishing in intensity and almost ceasing before the next irrigation.

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Assimilation and other processes favouring plant growth are especially rapid after an irrigation, gradually diminishing in intensity and almost ceasing before the next irrigation.

In the Utah experiments it was found that during the first week after the irrigation of peas, more than five hundred pounds of dry matter were added to the weight, and of oats, more than seven hundred pounds of dry matter were added to the acre.

The vigour and general condition of the plant depends largely upon the development of a good, deep root system. In the early stages of growth, the plant uses most of the materials gathered from the air and soil for the development of its root system. When these are well developed, carbon assimilation by the leaves is hastened and the growth is increased rapidly. Later in the life of the plant, the root growth becomes less, and the energies of the plant are more largely directed to the development of the parts above ground. When at last the stems are well developed and a sufficient quantity of material has been stored in the various plant organs the growth diminishes, first flowers and then seeds being developed. It is important, therefore, that as early as possible the root system be made large and well developed. To obtain this condition it is essential to keep the soil moderately wet in early spring. In districts where the winter rainfall is large, deep retentive soils will usually have sufficient water for the initial root development and no irrigation need be applied. If however the climate conditions are such that at seeding time the soil is not well

is not well filled with water, thorough irrigation immediately before or after planting is essential to a proper root development. The part of the plant above ground is also definitely affected by the quantity of water applied. As the water applied to the soil increases, the plant becomes longer. With a lack of water the plant remains short. Not only the stalks but also the proportion of leaves is distinctly affected by the amount of irrigation water applied.

In a grain crop the value of the straw is small in comparison with that of the seed. Hence as much of the plant as possible should be converted at harvest time into seed. On the other hand when a crop is grown for forage it is desirable to secure the largest proportions of leaves. The following extracts from various reports and papers fairly establishes the practices governing these basic principles of plant growth.

> *Alfalfa.* "Where the winter and spring precipitation is sufficient, or where winter irrigation has been practiced, soils which have good soil moisture retentive power need no irrigation before seeding the first crop, which in most localities generally occurs in the spring months after the danger of killing frosts is passed. Porous soils which have little retentive power for soil moisture usually require irrigation before seeding. After seeding the young alfalfa plants should receive no further irrigation until the plants show the need for water or even not until they show signs of suffering for lack of moisture; this is desirable to develop the root system

downward instead of confining it to the surface, as may occur with too early irrigation. The root system can be further strengthened by cutting the young alfalfa when eight inches high. When the alfalfa has established a well developed root system the common practice on retentive soil is to apply one irrigation before or after cutting. On gravelly porous soils and on shallow soils, two or even three irrigations for each cutting may be necessary."(6)

Cereals. "The soil should contain sufficient moisture at the time of seeding to germinate the seed and to start the plants growing. No irrigation before seeding is required for a retentive soil when winter precipitation is not too small, or when the soil moisture has been supplied by winter irrigation. Irrigation before seeding is necessary for a soil which is too dry because of deficient winter precipitation or irrigation. Where irrigation before seeding will keep the ground wet too long and delay the seeding, it may be necessary to irrigate immediately after planting. This practice is objectionable for soils that have a tendency to bake; it increases the evaporation loss and requires an earlier second irrigation.

After the plants have germinated, the first irrigation should not be applied until the plants require it, but before the plants begin to suffer for moisture, which for a moderately retentive soil will be two or three months after seeding when the plants shade the ground and have grown to a height of six to nine inches. A second irrigation is usually necessary when the heads just begin to form, and a third irrigation is often desirable when the heads are filling out. The practice will vary especially with the character of the soil and the time and extent of precipitation; a good reten-

tive deep soil with a moderate winter and spring precipitation may require only one late irrigation when the heads just begin to form; a porous soil may require four light irrigations."(6)

"In a number of irrigation experiments with grain the best results were obtained both in quantity and quality of yield with three irrigations at the jointing, booting and soft dough periods. At the jointing the embryo head is forming, at the booting it is about to emerge and at the soft dough the kernel is filling."(Harding)

"At the Utah Station the growth of wheat was divided into four stages (1) when five leaves had developed and the plants were 6"--8" high (2) the early boot stages when the plants were just swelling preparatory to heading (3) the bloom stage, when most of the plants were in bloom and (4) when the plants were in the dough stage. The experiments were conducted on a loam soil. The experiments were conducted on a loam soil. The precipitation averaged 17.8 inches and 37.3 bushels per acre were raised without irrigation. The highest yield of wheat was produced with three irrigations of five inches each applied at the five leaf, the early boot and the bloom stages. Irrigation applied after seeding before the grain was up and that applied after the dough stage, decreased the yield. Where only one irrigation was given the best time to give it was at the five leaf stage; where two irrigations were used the five leaf stage and boot stage were best; where three irrigations, the five leaf, boot and bloom stages were best." (Harding)

Potatoes. "Retentive soil except for late planting is usually sufficiently moist from the winter and spring precipitation to require no irrigation before

seeding. Dry soil must be irrigated before planting. Planting in dry hot soil, followed immediately by irrigation is not desirable. During the first stages of growth throughout cultivation is more important than irrigation, and no irrigation may be necessary until July. Too early irrigation after planting may compact and bake the soil around the roots. Potato vines are shallow rooted and frequent irrigations, especially early in the season when the water is cold, will retard the growth; for this reason some irrigators prefer to apply the water at night, when the soil and water have had all day to warm up in the sun. The moisture in the soil should be kept fairly uniform until the tubers begin to form, when a heavier irrigation is generally required. The soil should not be allowed to harden around the roots. The last irrigation should be applied before the growth of the tuber ceases, in order to give about 1½--2 months for ripening in dry earth. The number of irrigations will vary from two to four for sandy loam and from four to six light irrigations for a porous sandy soil or a shallow soil. The need of irrigation may be indicated by the appearance of the plants; dark leaves indicate a lack of moisture, light yellowish green leaves indicate an excess. An examination of the soil where the tubers form is another good indication. A sandy soil is in good condition when a ball of earth squeezed in the hand will retain its shape."(6)

Cotton. "Soils for cotton should be given sufficient moisture for germination before planting. With cultivation no further irrigation should be required for six weeks to two months. From two to four light irrigations are given during the period of plant growth. Too heavy irrigations at this time results in excessive vegetative growth at the expense of crop production. After about July 1st, the crop on most soils will re-

> quire irrigations at ten to fifteen days intervals. While some wilting in the early season may not be harmful, at the flowering period moisture should be maintained so that no wilting will occur. One or two irrigations after the first picking are usual." *(Harding)*

Orchards. Deciduous trees are deep rooted when the soil conditions are favourable; they require less water than other irrigated crops and for that reason the need for irrigation is not so apparent. Citrus trees are not as deep rooted as deciduous trees; they are evergreen and therefore the evaporation from their leaves is continuous and the maximum moisture need for fruit growth is in the fall; for these reasons citrus trees require more irrigation than deciduous trees.

Fall and winter irrigation is very advantageous in the maintenance of orchards, where the greater part of the rainfall does not occur in these periods. As a general rule trees must not be irrigated, or very cautiously, when they are in bloom, for such early irrigation is said to interfere with the setting of the fruit.

> "Orchard soils should not be allowed to dry out too much for an excessive dryness in early or middle summer will injure the tree for the whole season. On the other hand, over-irrigation tends to decrease fruit production and delay the ripening." (6)

The last irrigation is given in the first week of September, so that the new wood may have a chance to mature before any freezing occurs. This late irrigation also has the advantage of keeping the leaves somewhat longer on the trees, aiding thereby the formation of the new wood.

Young trees should not be irrigated more than once or twice a season. This is essential to the formation of a deep drought resisting root system. Professor Wickson draws the following conclusions:

> "For deciduous fruit trees on deep soils, fairly retentive, ten inches of irrigation water, applied at the proper time, during five months of growth and fruiting, accompanied by good cultivation, is sufficient, even when the rainfall is only about enough to prevent drying out during the winter.
>
> For citrus trees twenty inches of irrigation water is usually sufficient where the rainfall is considerable and for the more retentive soils, ten inches applied at the right time may be adequate."

A diversification of the irrigated crops will usually result in an increased duty. The reasonable water requirement should not be based on the needs of the crop of maximum water requirement but rather on the average water requirement for the entire ares,--the average being of course proportional to the areas which each type of crop occupies. By diversifying his crops the farmer's need for water will be

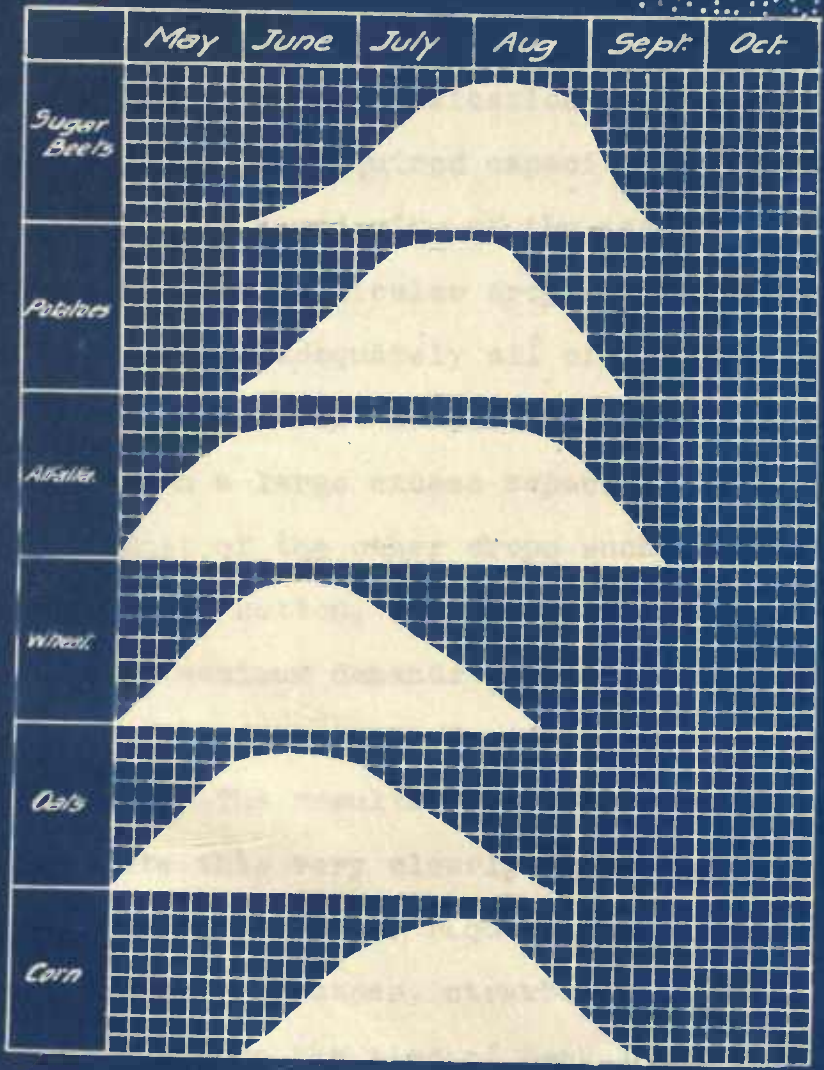

Diagram showing the Seasonal use of water by various crops in Cache Valley, Utah.

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FIG XVI

more uniform and constant, instead of the greatest need for water falling within a comparatively short period. The same applies to an entire irrigation project, helping materially in the proper distribution of water by rotation. The greater the diversification of the crop the more uniform will be the required capacity of the main canal.

If a majority of the acreage of any project is planted to one particular crop, say alfalfa, it is impossible to serve adequately all of the land in that crop at the time of greatest demand, unless the canal has been designed with a large excess capacity for that particular purpose. Most of the other crops such as grains, potatoes, corn, beans, cotton, etc., have a lower water requirement and their maximum demands do not extend over as long an interval of time as that of alfalfa or are not of the same magnitude. The results from the Cache Valley experiments illustrate this very clearly. (See Figure) In fact some of the crops of low water requirement such as fall planted grains, early potatoes, strawberries, etc., may be cared for entirely before the time of peak load. Other crops of low total water requirement, but which may require water during the peak of the season, are corn, beans, sorghums, etc. Potatoes and sugar beets may require as much water as alfalfa

during the two months of the peak loads, but on a given farm are not likely to require service at the same time.

In crop selection and carefully planned crop rotation may be found one of the most practical means of reducing the peak load of an irrigation system and maintaining a generally high water duty. If this peak can be distributed through the season, it will result in a lower construction cost, and in many economies in operation and maintenance.

CHAPTER IX

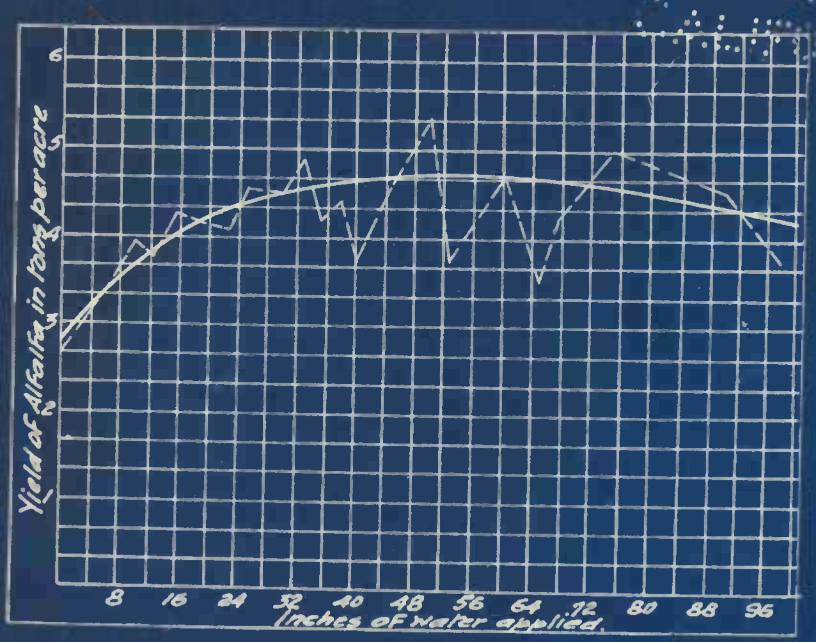
YIELD OF VARIOUS CROPS UNDER VARYING AMOUNTS OF IRRIGATION APPLICATIONS

Under the direction of Dr. Harris of Utah a very complete set of experiments has been conducted to determine the effect of varying quantities of water on the crop yield. The experiments were conducted in Cache Valley, Utah, and extend over a period of some fourteen to seventeen years. Whilst of course these results are strictly only of practical benefit to the area concerned, it nevertheless gives an accurate reflection of conditions under which a maximum of various crops may be obtained. The results obtained are reproduced below, together with results obtained from various other sources.

Irregularities in yield are often traceable to the fact that the complete series were not run through all the years. It must, therefore, be kept in mind that exact yields cannot be given too much weight. It will be much safer to take the results as a whole rather than any one figure or point on the curves. In the case of the Utah curves the actual average yield for the different irrigations are shown by the dotted lines, while the heavy line represents a medium yield obtained by considering the average of the great-

er number of tests to be nearer to the true average than the average of a fewer number and weighing accordingly. A one year test is not given the same weight in arriving at a point for the heavy curve to pass through as a test covering several years.

The following table shows the average of a total of one hundred seventy-six trials extending through fourteen years.



Yield of alfalfa with various quantities of irrigation water

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FIG XVII

The Utah results are tabulated in Table XXX and illustrated in Figure XVII. (13)

Alfalfa (Lucerne)

Acre inches water	Number of trials	Number of years	Yield in tons per acre
0	14	11	2,655
5	36	7	3,233
10	28	11	3,923
12.5	3	3	3,783
15	30	14	4,294
20	12	12	4,165
22.5	1	1	4.090
25	14	12	4.544
30	10	10	4.515
32.5	2	2	4.841
35	3	3	4.198
37.5	1	1	4.400
40	4	4	3.740
45	2	2	4.613
50	8	8	5.355
52.5	2	2	3.718
60	1	1	4.691
65	1	1	3.399
67.5	1	1	4.230
75	1	1	5.007
90	1	1	4.520
97.5	1	1	3.768

TABLE XXXI/18/

The results on alfalfa obtained at Davis are as follows:

No. of irrigations	Depth at each irrigation inches	Depth applied inches	Yield in Tons							Average value per acre at $7 per ton	Average cost of production per acre	Average profit per acre
			1910	1911	1912	1913	1914	1915	Average	$	$	$
0	--	--	3.85	5.94	5.52	2.75	2.89	2.35	3.88	27.16	8.73	18.43
2	6	12	4.78	7.52	6.51	4.31	5.83	4.84	5.63	39.41	15.37	24.04
3	6	18	--	--	7.02	5.69	8.02	6.46	6.80	47.00	19.35	28.25
4	6	24	6.00	8.38	8.32	6.89	9.96	7.96	7.92	55.44	23.22	32.22
4	7.5	30	7.53	9.54	9.43	7.97	11.06	8.32	8.98	62.86	26.45	36.41
4	9	36	7.58	9.33	9.38	8.22	12.48	8.63	9.27	64,89	27.96	36.93
4	12	48	8.45	9.52	8.63	8.83	10.62	8.05	9.02	63.14	29.10	34.04
4	15	60	--	--	10.17	7.25	10.70	5.55	8.42	58.94	29.44	29.50

In the Modesto Turlock district investigations were conducted during the years 1916, 1917 and 1918. The results are shown in the following Table.

TABLE XXXII*(23)*

Check No.	1916		1917		1918	
	Amount of water applied inches	Total yield tons per acre	Amount of water applied inches	Total yield tons per acre	Amount of water applied inches	Total yield tons per acre
1	30.04	7.68	--	--	41.86	6.64
2	36.05	8.74	68.44	6.73	55.01	5.06
3	22.06	8.01	29.42	6.92	45.44	6.17
4	17.21	7.91	21.59	6.94	18.45	6.41
5	25.25	8.91	29.75	6.96	38.71	6.58
6	22.39	8.73	35.12	7.09	28.11	6.75
7	29.41	9.52	44.42	7.00	47.75	6.43
8	28.93	9.56	45.64	7.64	36.99	6.63
9	26.72	8.9	47.77	4.25	41.93	5.71

In Oregon--at Corvallis--similar experiments were conducted for the purpose "of determining the value of irrigation for increasing and insuring productiveness of the agricultural lands in the semi-humid Willamette Valley."

The following Table shows the results on Alfalfa

TABLE XXXIII (111)

Year and Treatment	Total yield in tons per acre
A. Value of harrowing and irrigating for new seeding	
1911 (seeded 1909 without irrigation)	2.17
1911 (seeded 1909 with irrigation harrowed)	4.16
1911 (seeded 1909 with irrigation unharrowed)	4.08
1912 (seeded 1909 without irrigation)	4.00
1912 (seeded 1909 with irrigation harrowed)	5.42
1912 (seeded 1909 with irrigation unharrowed)	4.10
B. Irrigation before and after cutting	
1911 6" before cutting	4.41
1911 6" after cutting	4.59
1912 2 irrigations of 5" before cutting	10.37
1912 2 irrigations of 5" after cutting	10.30
C. Furrows versus flooding	
1912 one 5" irrigation with furrows	6.37
1912 one 5" irrigation with furrows	5.17
D. Amount of irrigation	
1911 2 irrigations of 4", total 8"	4.51
1911 3 irrigations of 4", total 12"	5.22
1912 2 irrigations of 4", total 8"	6.70
1912 2 irrigations of 6", total 12"	7.75
1913 (seeded 1909 without irrigation)	2.15
1913 1 irrigation of 4", total 4"	3.80
1913 1 irrigation of 6", total 6"	4.22
1913 2 irrigations of 4", total 8"	4.22

Alfalfa was weighed as green feed in 1912 and as cured hay in 1911 and 1913.

The experiments conducted at Idaho during 1910 --1914 give the following summarized results.

TABLE XXXIV *(Harding)*

Class of soil	Average depth of water applied in feet	Average yield in tons per acre
Clay loam areas	2.40	4.91
Areas making maximum yield in each experiment	2.73	5.47

An examination of the results for alfalfa shows that this crop can profitably use much larger quantities of water than most other crops grown under irrigation. There is a decline in yield after a certain maximum amount of water is applied, but the decline is slow. Alfalfa is seen to be much less sensitive to over irrigation than potatoes and cereals. The Utah results show a maximum yield with fifty acre inches, although twenty-five inches gave very nearly the same amount i. e. a saving of fifty percent of water gave only a 15.2 percent decrease in crop yield.

In the case of the Davis experiments at the end of the six year experimental period, the stand on the areas given the heaviest irrigations was only 27 percent of the original stand, the excess use having enabled grass to come

into the alfalfa. The best stands at the end were areas given thirty to thirty-six inches of water,--which is undoubtedly the most desirable quantity for the irrigation of alfalfa under general Sacramento Valley and San Joaquin Valley conditions.

In 1918 the best yield at Modesto was with a total depth of 28.11 inches.

In Oregon Professor Powers comes to the following conclusion, "The maximum yield of alfalfa in all trials has been secured in the dry seasons with ten or twelve inches of water, but in wet seasons with six inches of water. The most economical increase in yield with irrigation has been secured with four to six inches of water."

Potatoes. Table XXXV and Figure XVIII show the Utah results for this crop. Although considerable variation is noted in the trials during the different years (the experiments extended through fourteen years and the Table shows the average of two hundred sixteen trials), the general tendencies are distinct. The most favourable amount of water for potatoes seems to be between thirty and forty inches. For applications above sixty inches the yield drops very rapidly. This is probably due in part to the fact that excessive water prevents the tubers from securing the supply of air needed for optimum growth.

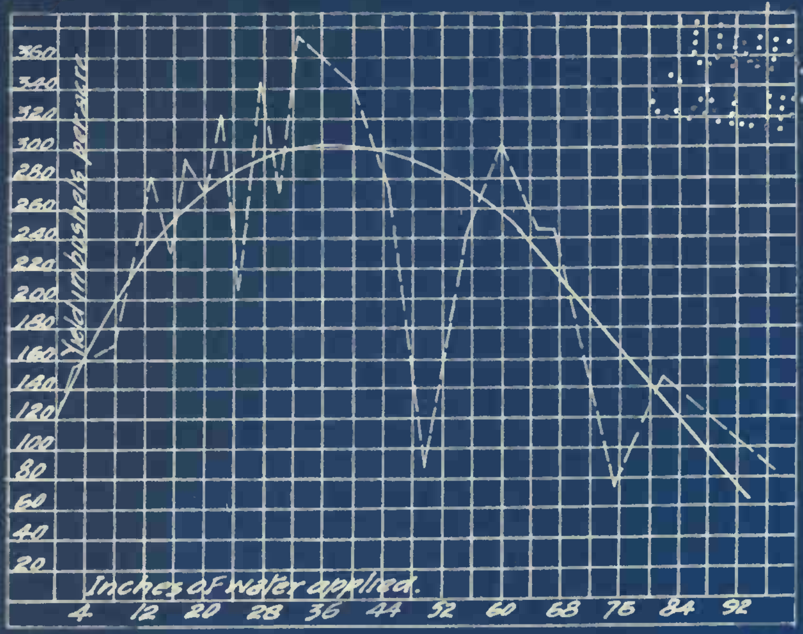

FIG XVIII

Yield of potatoes with various quantities of irrigation water.
Cache Valley, Utah.
Utah Ag. Coll. Bul. 173

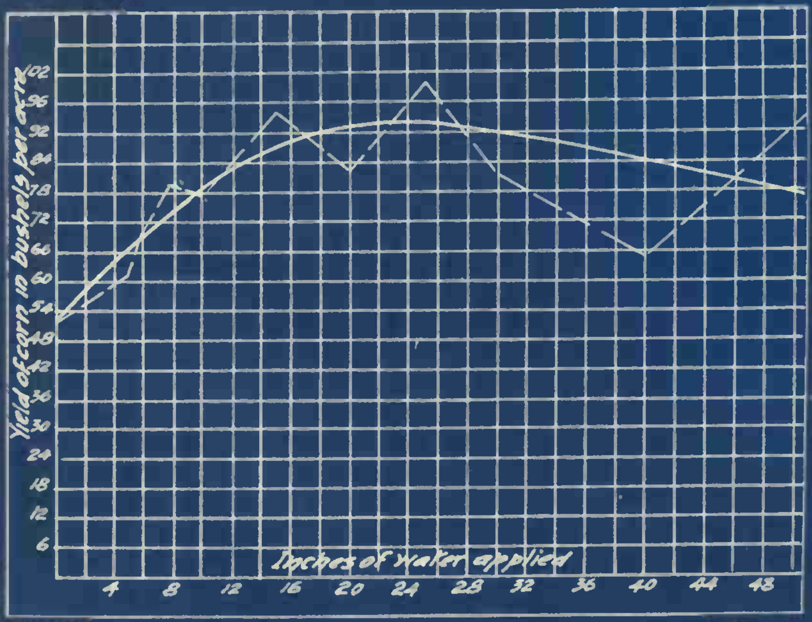

FIG XIX

Yield of corn with various quantities of irrigation water.
Utah Ag. Coll. Bul. 173

TABLE XXXV(13)

Acre inches applied	No. of trials	No. of years	Yield in bushels per acre
None	12	12	117.37
2.5	4	4	157.19
5.0	39	14	162.23
7.5	20	9	165.38
10	39	14	217.24
12.5	4	4	284.87
15	39	14	228.62
17.5	1	1	293.75
20	13	13	266.53
22.5	2	2	321.18
25	4	4	204.02
27.5	2	2	345.50
30	7	7	269.92
32.5	4	4	377.59
40	2	2	341.44
45	8	8	271.39
50	1	1	83.45
55	3	3	240.00
60	6	6	304.00
65	1	1	246.00
67.5	1	1	245.00
75	1	1	149.00
82.5	2	2	149.00
97.5	1	1	85.00

The Oregon results are as follows:

TABLE XXXVI(11)

Year and Treatment	Yield in bushels per acre
<u>1911--a dry season</u>	
Dry	135.1
3 irrigations of 1"	250.9
1 " " 3"	176.4
2 " " 2½"	240.7
1 " " 5"	190.9
3 " " 2"	254.9
2 " " 3"	258.1
2 " " 3"	308.5
3 " " 3"	292.5
<u>1913--wet season</u>	
Dry	109.8
1 irrigation of 2"	172.2
1 " " 3"	213.3
2 " " 2"	145.2

The average results with potatoes at Gooding, Idaho, for the four years, 1910--1914 are in Table XXXVII.

TABLE XXXVII *(Harding)*

No. of irrigations	Total water applied in feet	Yield tons per acre
2	.69	3.2
4	1.72	6.75
6	2.83	6.7

In Oregon the maximum yield for the wet season was with three inches of water, while in the dry season it was with six inches of water. The most economical yield of potatoes obtained in the course of the experiments was secured with the aid of three one inch irrigations, applied ten days apart, giving a yield of 38.6 bushels per acre inch.

In Idaho, the conclusion was reached that it would not be advisable or profitable to apply more than two to two and one-half acre feet per acre on clay loam soils.

Cereals. Experiments at Utah on corn were conducted through a period of seventeen years with the following results, given in Table XXXVIII and Figure XIX.

TABLE XXXVIII(13)

Acre inches applied	No. of trials	No. of years	Yield in bushels per acre
None	13	13	57.33
5	13	13	61.39
7.5	8	8	79.14
10	17	17	77.23
15	8	8	93.93
20	17	17	81.80
25	8	8	99.16
30	17	17	81.49
40	9	9	65.30
55	8	8	96.78

On the San Joaquin and King's River Canal system the following results were obtained.

TABLE XXXIX

Year	Depth of water applied in feet
1907	2.13
1908	1.65
1911	1.38
Average	1.72

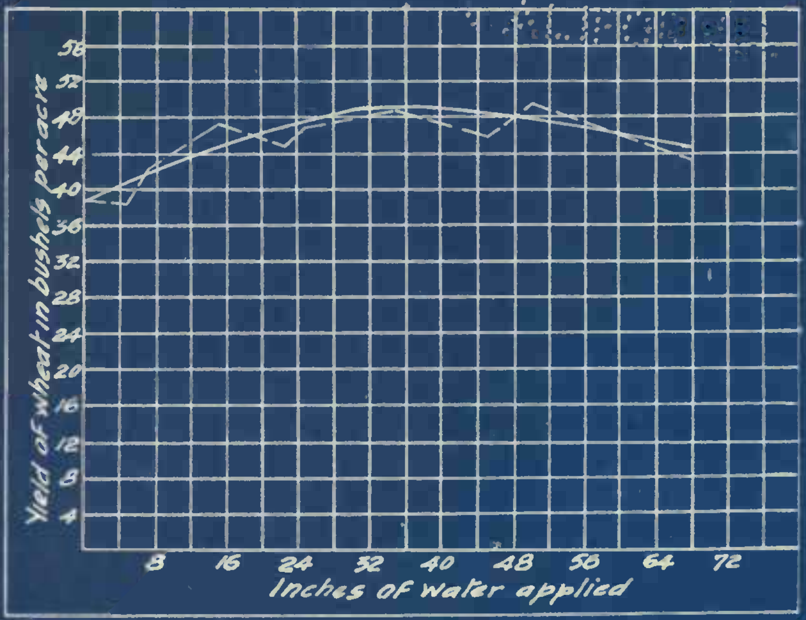

FIG. XX

Yield of wheat with various quantities of irrigation water.
Utah Ag. Coll. Bul. 173

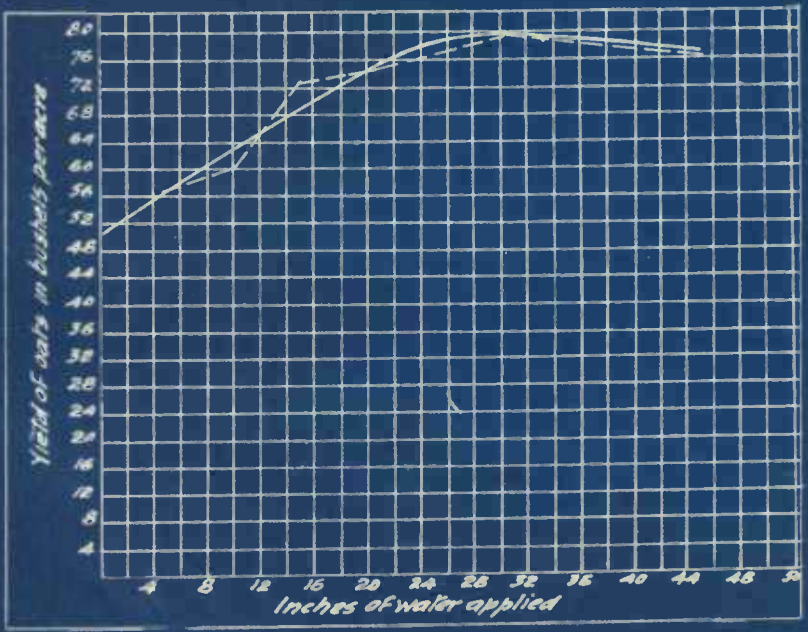

FIG. XXI

Yield of oats with various quantities of irrigation water.
Utah Ag. Coll. Bul. 173

The Utah results on wheat, extending through a period of thirteen years are given in Table XL and Figure XX.

TABLE XL(13)

Acre inches applied	No. of trials	No. of years	Yield per acre	
			Grain bushels	Straw pounds
None	9	9	38.37	3982
5	34	13	38.23	3540
7.5	18	9	41.54	3301
10	38	13	42.90	4142
15	34	13	47.10	4796
20	4	4	45.70	5940
22.5	4	4	44.60	6757
25	18	9	46.46	4311
35	18	9	48.55	4755
45	4	4	45.80	6250
50	18	9	49.38	5332
67.5	4	4	43.50	5794

The experiments at Gooding, Idaho, gave the following results.

TABLE XLI *(Harding)*

No. of irrigations	Total water absorbed per acre foot per acre	Yield of grain bushels per acre
0	0	13.3
1	.36	23.3
3	.75	28.7
4	1.23	31.8
6	1.76	33.1
8	2.27	36.0
9	2.94	27.5

Results on wheat experiments at Davis, California, during 1912-1914 gave the following:

TABLE XLII

No. of irrigations	Depth applied inches	Yield in pounds per acre	
		Hay	Grain
0	--	2703	637
1	6.0	4267	1157
2	10.1	6100	1529
2	15.5	5050	1029

Typical practice is represented by Table XLIII which shows the net duty on grain in the San Joaquin Valley

TABLE XLIII

Year	Depth applied ft.
1907	.74
1908	.84
1911	.96
1913	1.11
Average	.91 ft

At Utah, oats gave the following results for a period of six years--Table XLIV and Figure XXI.

TABLE XLIV (13)

Acre inches applied	No. of trials	No. of years	Yield per acre	
			Grain in bushels	Straw in pounds
None	6	6	50.37	1876
5	21	6	57.51	2077
10	18	6	60.18	2107
15	18	6	72.82	2563
20	6	6	74.40	2723
30	3	3	79.90	2774
45	6	6	76.68	3149

On the whole it will be seen that the yield of cereals is not nearly so much affected by irrigation as is the case with potatoes and alfalfa. In the case of the Utah experiments on wheat, for instance, fifteen inches of water gave almost as high a yield as any treatment and yet the yield kept up fairly well with the very heavy irrigations. It will be noted that where no irrigation water was applied the yield of wheat were fairly satisfactory. Therefore, in practice, it is doubtful whether more than fifteen inches of water would pay for the extra yield obtained.

Oats is a plant which is more sensitive to moisture than wheat. In the Utah results, there is a gradual

increase in the yield with an increase in water up to thirty inches, above which the yield decreases slightly. The yields were not greatly different for quantities of water between fifteen and forty-five acre inches.

The results on corn show the highest yield with twenty-five inches of water, although yields are almost the same for all quantities of water between fifteen and thirty inches. While the yields were somewhat reduced by excessively large irrigation applications, this was not nearly so much the case as with potatoes.

Citrus Fruits. In the State Engineers Report (California) for 1912--1914, the following data of the net duty on citrus fruits in Southern California are given.

TABLE XLV

Location and Source of Supply	Year	Acreage	Depth of water applied feet
Gage Canal and Riverside Water Companies	1899-1905	80,667	2.25
Riverside Water Company	1901-1908	9,000	2.29
Riverside Water Company	1912	31.5	4.10
Riverside Water Company	1912	19	2.58
Santa Ana Valley Canal	1912	20	1.79
Santa Ana Valley Canal	1912	18.4	1.52
Del Monte Irrigation Company	1906	2,000	.73
Del Monte Irrigation Company	1907	2,000	1.10
Del Monte Irrigation Company	1908	2,000	.73
Del Monte Irrigation Company	1909	2,000	.73
Palomares Irrigation Company	1906	600	.71
Palomares Irrigation Company	1907	600	.83
Palomares Irrigation Company	1908	600	.83
Palomares Irrigation Company	1909	600	.83

Deciduous Orchards and Vineyards

TABLE XLVI

Location and source of supply	Year	Acreage	Depth applied feet	Remarks
Sierra Foothills				
South Yuba Water Co.	1909	6,900	2.62	
Bear River Canal	1909	5,000	2.62	
Sacramento Valley				
Palermo Land & Water Co.	1912	33	.75	Prunes
Palermo Land & Water Co.	1912	10.5	1.64	Olives
Palermo Land & Water Co.	1912	10	.80	Olives and Peaches
Yolo Water & Power Co.	1913	14.2	2.29	Prunes
Orland Project	1914	14.2	.25	Young Almonds
San Joaquin Valley				
Turlock Canal	1909	37.8	.38	One irrigation
Pumping plants at Madera	1910	222	.86	No irrigation
Fresno Canal	1910	160	.49	One irrigation
San Joaquin & Kings River Canal	1906--07	104	2.64	
San Joaquin & Kings River Canal	1907--08	15	2.38	
Pumping plants at Friant	1912	20	.83	Two irrigations
Pumping plants at Friant	1912	150	.06	
Southern California				
Santa Ana Valley Canal	1912	15	4.83	Walnuts
Santa Ana Valley Canal	1912	21	3.18	Walnuts

Chart showing the location of various Irrigation schemes in the U.S.A.

FIG XXII

CHAPTER X

TABLE XLVII

Showing the gross and net duty for various irrigation projects in the U. S. A. for the year 1917.

Project scheme	Amount diverted	Amount wasted acre feet	Amount lost acre feet	Amount applied acre feet	Acerage	Per-cent ap-plied	Per-cent wast-ed	Per-cent lost	Gross duty	Net duty
Salt River	994,733	22,067	435,155	537,511	201,601	54	2.3	43.7	4.93	2.67
Yuma River	337,597	115,715	85,351	136,531	36,956	40.6	34.2	25.2	10.55	3.70
Orland Project	74,032	9,373	20,210	44,449	12,729	60.1	12.6	27.3	5.82	3.49
Boise Project	585,205	16,858	209,864	358,483	116,686	61.3	2.9	35.8	5.02	3.07
Minnidoka North	365,331	7,843	178,474	179,014	50,479	49.1	2.0	48.9	7.24	3.55
Minnidoka South	238,886	22,241	87,403	129,242	43,220	54.0	9.3	36.7	5.54	2.99
North Platte	388,963	4,282	160,849	177,472	83,203	45.5	13.3	41.2	4.68	2.13
Truckee Carson	263,432	53,036	85,021	125,375	40,392	47.6	20.1	32.3	6.53	3.11
Carlsbad	95,196	1,144	54,463	39,589	16,882	41.6	1.2	57.2	5.53	2.33

TABLE XLVIII(39)

Showing detailed information in regard to the net duty and distribution of irrigation water on various Irrigation Projects in the U. S. A. for the years 1912--1919. (See Figure XXII)

Project	Year	Total area irrigated	Total quantity water diverted for direct use acre feet	Total quantity delivered to farms acre feet	Acre feet per acre delivered to farms	Total annual rainfall feet	Rainfall during irrigation season feet	Percentage of area in different crops				
								Cereals and seed	Hay and forage	Fruit and nuts	Vegetables and truck	Miscellaneous
Yuma Project	1912	13,767	96,409	67,273	4.59	.26	.26	39	56	--	3	2
	1913	19,607	127,307	85,411	4.36	.09	.09	26	39	--	1	34
	1914	25,207	215,207	93,167	3.69	.20	.20	34	58	--	1	7
	1915	27,857	246,786	92,897	3.34	.36	.36	46	50	--	2	21
	1916	29,483	249,723	94,393	3.20	.20	.20	32	47	--	1	20
	1917	36,956	337,597	136,531	3.70	.18	.18	31	35	--	3	31
	1918	45,670	314,900	150,229	3.30	.24	.24	19	24	--		57
	1919	53,284	478,185	155,417	2.90	.17	.17	22	27	--		51
				Miscellaneous--principally cotton and cotton seed								
Orland Project	1912	4,230	34,000	16,700	3.95	1.32	.60	1	95	3	1	
	1913	6,617	40,350	19,850	3.00	1.75	.29	--	97	1	1	1
	1914	7,354	50,000	30,000	4.08	1.80	.26	1	95	3	1	--
	1915	8,928	52,347	30,374	3.40	2.34	.28	3	92	4	1	--
	1916	9,357	60,003	38,105	4.07	1.36	.16	8	86	4	2	--
	1917	12,729	74,032	44,449	3.49	.83	.51	20	71	4	4	1
	1918	14,764	45,900	28,300	2.91	1.37	.61	30	66	3	1	2
	1919	15,203	72,000	45,000	2.95	.94	.24	30	65	4		--

Project	Year	Total area irrigated	Total quantity water diverted for direct use acre feet	Total quantity delivered to farms acre feet	Acre feet per acre delivered to farms	Total annual rainfall feet	Rainfall during irrigation season feet	Percentage of area in different crops				
								Cereals and seed	Hay and forage	Fruit and nuts	Vegetables and truck	Miscellaneous
Uncompahgre Project	1912	27,887	140,601	133,912	4.81	.91	.59	26	42	7	18	7
	1913	31,428	168,573	160,056	5.09	.67	.33	29	39	6	18	8
	1914	33,873	185,227	171,268	5.05	1.10	.74	35	41	6	15	3
	1915	41,463	264,060	231,271	5.56	.75	.47	35	45	5	10	5
	1916	49,273	329,554	299,432	6.08	1.09	.94	36	46	5	9	4
	1917	53,108	368,148	316,365	5.96	.65	.52	33	41	5	16	5
	1918	58,270	423,050	367,144	6.30	.92	.55	36	43	4	14	3
	1919	60,906	420,176	390,770	6.42	--	.45	33	48	4	12	3
Boise Project	1912	65,042	244,000	122,644	1.89	1.51	.84	51	45	--	4	--
	1913	76,265	328,174	180,217	2.38	1.34	.63	55	40	--	4	1
	1914	83,714	410,912	219,695	2.62	.72	.47	49	47	1	3	--
	1915	97,127	448,029	272,659	2.81	1.11	.57	52	44	1	3	--
	1916	101,316	607,180	360,907	3.56	1.22	.54	46	50	2	2	--
	1917	116,686	585,205	358,483	3.07	1.21	.58	41	51	4	3	1
	1918	110,000	824,462	--	3.75	1.06	.60	44	51	3	2	--
	1919	125,000	759,089	--	3.34	.95	.29	40	53	3	3	1

Project	Year	Total area irrigated	Total quantity water diverted for direct use acre feet	Total quantity delivered to farms acre feet	Acre feet per acre delivered to farms	Total annual rainfall feet	Rainfall during irrigation season feet	Percentage of area in different crops				
								Cereals and seed	Hay and forage	Fruit and nuts	Vegetables and truck	Miscellaneous
Hunt-	1912	14,425	49,056	21,438	1.48	1.52	.92	30	30	--	2	38
ley	1913	15,798	34,696	24,118	1.53	1.04	.62	37	33	--	2	8
Proj-	1914	17,068	36,595	24,428	1.43	1.03	.75	34	38	--	3	25
ect	1915	18,203	33,487	17,634	.97	1.44	1.19	33	37	--	2	28
	1916	18,800	45,044	21,123	1.12	.97	.61	31	39	--	1	29
	1917	19,122	43,563	21,274	1.12	.97	.34	38	42	--	3	17
	1918	19,262	47,982	20,182	1.06	1.06	.66	45	42	--	2	11
	1919	19,310	92,638	31,785	1.64	.91	.56	37	59	--	--	4
				Miscellaneous--principally sugar beets								
Milk	1912	352	1,256	293	.83	1.46	.37	89	10	--	1	--
Riv-	1913	2,545	4,267	2,349	.92	.96	.84	66	34	--	--	--
er	1914	2,201	3,276	1,760	.80	1.12	.77	56	43	--	1	--
Proj-	1915	4,193	13,041	2,884	.70	1.34	1.14	39	60	--	1	--
ect	1916	5,518	13,138	3,700	.68	1.31	.84	25	75	--	--	--
	1917	11,058	30,905	11,195	1.01	.73	.33	38	67	--	1	--
	1918	24,843	74,924	16,900	.68	.87	.61	31	66	--	1	--
	1919	25,584	72,775	21,400	.84	.77	.47	19	80	--	1	--

Project	Year	Total area irrigated	Total quantity water diverted for direct use acre feet	Total quantity delivered to farms acre feet	Acre feet per acre delivered to farms	Total annual rainfall feet	Rainfall during irrigation season feet	Percentage of area in different crops				
								Cereals and seed	Hay and forage	Fruit and nuts	Vegetables and truck	Miscellaneous
Sun River Project	1912	6,824	20,392	11,688	1.71	.82	.63	73	23	--	4	--
	1913	7,419	24,628	11,187	1.51	1.02	.60	60	37	--	3	--
	1914	6,613	24,763	11,468	1.74	.91	.54	46	51	--	3	--
	1915	4,243	15,538	4,654	1.10	1.35	1.15	33	64	--	3	--
	1916	4,717	17,841	5,757	1.22	1.42	1.13	24 26	71	--	2	1
	1917	6,675	25,481	9,091	1.35	.81	.59	24	72	--	3	1
	1918	7,569	30,087	11,193	1.48	.59	.49	36	64	--	--	--
	1919	11,496	42,863	24,000	1.90	.60	.47	19	80	--	1	--
Lower Yellowstone Project	1912	5,068	15,432	6,058	1.19	1.57	.85	87	12	--	1	--
	1913	7,660	30,088	10,250	1.34	.90	.60	76	22	--	1	1
	1914	5,743	25,769	9,143	1.59	1.16	.93	41	55	--	3	1
	1915	12,656	40,141	17,970	1.42	1.48	1.09	57	42	--	1	1
	1916	6,020	27,181	7,545	1.25	1.60	1.28	40	59	--	1	--
	1917	15,744	60,205	27,842	1.77	.73	.35	41	53	--	2	4
	1918	21,075	51,445	23,321	1.11	1.13	.72	53	47	--	--	--
	1919	21,300	70,029	26,252	1.23	.80	.44	45	53	--	1	1

Project	Year	Total area irrigated	Total quantity water diverted for direct use acre feet	Total quantity delivered to farms acre feet	Acre feet per acre delivered to farms	Total annual rainfall feet	Rainfall during irrigation season feet	Percentage of area in different crops				
								Cereals and seed	Hay and forage	Fruit and nuts	Vegetables and truck	Miscellaneous
North Platte Project	1912	50,250	239,588	113,251	2.25	1.65	1.23	53	41	--	2	4
	1913	56,829	297,045	141,489	2.49	1.34	1.07	38		--	3	7
	1914	60,532	415,980	176,915	2.92	.84	.50	30	60	--	2	8
	1915	70,000	294,188	96,467	1.38	1.91	1.34	32	52	--	3	13
	1916	75,620	443,256	164,240	2.18	.85	.60	35	50	--	3	12
	1917	83,203	388,963	177,472	2.13	.98	.70	29	49	--	9	13
	1918	97,908	--	204,819	2.31	1.66	.45	36	48	--	9	7
	1919	99,418	--	201,505	2.27	.96	.13	38	42	--	8	12
Truckee Carson Project	1912	25,050	243,913	62,707	2.50	.34	.31	13	83	1	2	1
	1913	30,857	186,175	69,798	2.26	.67	.52	8	88	--	1	3
	1914	28,651	268,028	94,730	3.29	.34	.09	7	91	--	2	--
	1915	40,295	233,691	118,233	2.94	.52	.35	12	83	--	5	--
	1916	39,400	264,185	130,792	3.32	.44	.10	12	86	--	2	--
	1917	40,392	263,432	125,375	3.11	.23	.09	9	84	--	2	5
	1918	42,311	266,927	126,545	2.99	.53	.42	13	85	--	2	--
	1919	44,324	317,424	134,015	3.02	.24	.18	13	85	--	2	--

Project	Year	Total area irrigated	Total quantity water diverted for direct use acre feet	Total quantity delivered to farms acre feet	Acre feet per acre delivered to farms	Total annual rainfall feet	Rainfall during irrigation season feet	Percentage of area in different crops				
								Cereals and seed	Hay and forage	Fruit and nuts	Vegetables and truck	Miscellaneous
Carlsbad Project	1912	13,459	85,086	38,764	2.88	1.06	.95	36	52	1	--	11
	1913	14,260	86,560	33,044	2.32	1.28	1.17	26	49	1	--	24
	1914	12,690	87,900	30,900	2.44	1.59	1.21	12	73	1	1	13
	1915	13,470	79,530	28,857	2.14	1.55	1.22	27	67	--	1	5
	1916	16,600	105,470	40,382	2.43	1.66	1.65	27	44	1	--	28
	1917	16,882	95,196	39,589	2.33	.28	.28	36	45	--	1	18
	1918	19,462	98,920	47,380	2.43	.64	.62	26	53	--	--	17
	1919	20,363	114,050	48,933	2.40	1.58	1.58	5	55	--	--	40
			Miscellaneous--principally cotton and cotton seed									
Rio Grande Project	1912	23,115		(Not available)				22	72	2	1	3
	1913	27,723	144,610	120,603	4.34	.59	.41	19	70	2	5	4
	1914	28,442	216,920	161,552	5.68	1.42	1.00	23	67	2	8	--
	1915	33,876	256,189	199,952	5.90	.85	.74	20	72	2	6	--
	1916	62,513	488,286	420,646	6.72	.65	.52	29	63	2	6	--
	1917	65,947	646,075	552,392	8.38	.54	.54	26	45	2	--	27
	1918	64,781	613,638	348,296	5.37	.68	.68	35	50	1	5	9
	1919	70,012	603,711	174,945	2.5	.82	.82	15	62	3	9	11

Project	Year	Total area irrigated	Total quantity water diverted for direct use acre feet	Total quantity delivered to farms acre feet	Acre feet per acre delivered to farms	Total annual rainfall feet	Rainfall during irrigation season feet	Percentage of area in different crops				
								Cereals and seed	Hay and forage	Fruit and nuts	Vegetables and truck	Miscellaneous
Umatilla	1912	4,600	54,256	37,950	8.25	.90	.42	--	84	2	12	2
	1913	5,000	59,552	42,250	8.45	.79	.28	2	83	8	5	2
	1914	5,100	62,728	36,300	17.11	.55	.21	2	86	7	4	1
	1915	5,300	55,333	29,552	5.57	.87	.48	6	82	6	3	3
	1916	5,500	56,708	31,557	5.73	1.02	.33	3	87	7	2	1
	1917	7,327	86,977	45,367	6.19	.67	.31	3	83	8	3	3
	1918	9,100	118,154	48,163	5.61	.55	.29	5	86	7	--	2
	1919	10,533	162,850	53,500	5.1	.79	.30	2	87	8	2	1
Klamath	1912	23,834	42,087	26.929	1.13	1.63	.61	34	54	--	3	9
	1913	18,928	38,005	22,161	1.7	1.34	.50	33	65	--	2	--
	1914	24,440	53,428	30,672	1.26	.95	.25	33	65	--	2	--
	1915	27,254	69,970	30,642	1.12	.98	.29	40	58	--	2	--
	1916	29,351	66,010	29,970	1.02	.91	.27	41	58	--	1	--
	1917	33,365	65,368	32,780	.98	.84	.15	39	60	--	--	1
	1918	33,268	104,926	52,090	1.36	--	.20	29	67	--	1	3
	1919	37,881	119,850	56,490	1.32	--	.11	25	75	--	--	--

Project	Year	Total area irrigated	Total quantity water diverted for direct use	Total quantity delivered to farms acre feet	Acre feet per acre delivered to farms	Total annual rainfall feet	Rainfall during irrigation season feet	Percentage of area in different crops				
								Cereals and seed	Hay and forage	Fruit and nuts	Vegetables and truck	Miscellaneous
Belle Fourche	1912	27,897	57,715	30,390	1.09	1.42	.93	68	25	--	1	6
	1913	32,881	95,879	47,349	1.44	1.17	.78	66	30	--	2	2
	1914	37,454	110,461	54,262	1.45	1.07	.64	56	43	--	1	--
	1915	44,067	47,968	16,484	.37	1.77	1.58	43	56	--	11	--
	1916	48,468	153,594	39,132	.81	1.26	.86	45	53	--	1	1
	1917	50,272	113,314	61,134	1.22	.83	.20	23	60	--	1	6
	1918	52,445	190,844	51,731	.99	1.46	.85	33	63	--	1	3
	1919	56,225	121,293	82,409	1.46	.96	.47	23	73	--	1	3
O'Kanogan	1912	7,260	17,319	9,040	1.24	1.49	.49	22	35	27	15	1
	1913	7,700	19,497	11,993	1.56	.91	.48	7	50	31	11	1
	1914	7,740	32,234	20,035	2.59	1.03	.25	2	41	50	6	1
	1915	7,800	24,640	18,580	2.38	1.33	.50	1	35	62	3	--
	1916	7,850	25,947	19,615	2.50	1.05	.57	1	31	65	3	--
	1917	8,000	25,182	19,900	2.49	.72	.17	2	29	62	5	2
	1918	6,402	9,770	6,339	.99	.84	.47	1	29	61	3	2
	1919	5,849	12,844	9,967	1.70	.89	.42	--	27	69	2	2

Project	Year	Total area irrigated	Total quantity water diverted for direct use	Total quantity delivered to farms acre feet	Acre feet per acre delivered to farms	Total annual rainfall feet	Rainfall during irrigation season feet	Percentage of area in different crops				
								Cereals and seed	Hay and forage	Fruit and nuts	Vegetables and truck	Miscellaneous
Shoshone	1912	16,524	49,307	27,370	1.65	.59	3.51	43	54	--	3	--
	1913	19,423	68,894	40,436	2.08	.41	.37	34	64	--	2	--
	1914	22,226	91,708	52,789	2.38	.49	.48	33	65	--	1	1
	1915	25,753	95,957	54,668	2.12	.77	.72	38	56	--	2	4
	1916	29,977	125,662	70,247	2.35	.39	.25	43	52	--	2	3
	1917	32,764	110,916	68,738	2.10	.58	.46	44	50	--	3	3
	1918	38,282	162,463	84,378	2.29	.57	--	48	44	--	3	5
	1919	41,641	199,061	117,459	2.81	.04	--	48	46	--	4	2
Imperial Valley	1912	100,681	---	318,122	3.19	--	--	44	47	1	3	5
	1913	101,796	---	337,349	3.31	--	--	32	58	1	3	6
	1914	105,902	---	358,579	3.38	--	--	26	52	1	4	17
	1915	108,224	---	336,435	3.11	--	--	39	48	2	5	6
	1916	105,702	---	350,582	3.33	--	--	30	42	2	5	21
	1917	113,503	---	364,578	3.21	--	--	33	31	2	7	27
	1918	123,915	---	366,694	2.96	--	--	38	30	2	4	26

Project	Year	Total area irrigated	Total quantity water diverted for direct use	Total quantity delivered to farms acre feet	Acre feet per acre delivered to farms	Total annual rainfall feet	Rainfall during irrigation season feet	Percentage of area in different crops				
								Cereals and seed	Hay and forage	Fruit and nuts	Vegetables and truck	Miscellaneous
Sunnyside	1912	62,800	307,585	192,983	3.17	.72	.42	10	60	15	9	6
	1913	64,400	320,512	204,940	3.18	.57	.28	10	60	18	11	1
	1914	66,525	309,903	204,504	3.07	.69	.41	12	59	19	9	1
	1915	68,840	272,401	168,852	2.45	.69	.25	18	54	19	9	--
	1916	73,000	349,262	239,898	3.29	.60	.20	15	56	22	7	--
	1917	80,500	385,179	254,280	3.16	.46	.17	13	50	12	11	7
	1918	84,650	415,097	290,502	3.43	.45	.24	13	52	16	8	11
	1919	90,000	421,364	295,215	3.27	.43	.14	14	60	17	6	3
Tieton	1912	15,008	47 47,675	34,445	2.29	.86	.20	16	39	2	41	2
	1913	18,750	59,509	42,539	2.27	.66	.19	20	41	5	31	3
	1914	20,600	67,788	43,099	2.09	.82	.26	24	45	6	23	2
	1915	22,000	62,000	40,376	1.84	1.01	.23	28	45	12	13	2
	1916	23,000	75,911	49,412	2.15	.75	.21	25	48	18	8	1
	1917	25,400	80,377	57,318	2.25	.58	.10	22	44	22	10	2
	1918	26,400	90,280	64,068	2.43	.45	.29	21	45	27	7	--
	1919	27,000	98,223	70,776	2.62	.57	--	17	49	28	4	2

TABLE XLIX

Average Seasonal Duty of Water on various Reclamation Service Projects 1912-1917 (inclusive)

Scheme	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Salt River	.08	.14	.26	.30	.38	.37	.34	.33	.31	.20	.12	.05	2.90
Yuma	.11	.20	.35	.35	.38	.45	.47	.49	.44	.24	.15	.13	3.81
Orland		.01	.08	.29	.61	.72	.73	.65	.42	.13			3.66
Uncompahgre				.17	.91	1.14	1.10	.97	.72	.42			5.43
Boise				.16	.46	.67	.68	.45	.26	.04			2.72
Minnidoka North				.14	.75	1.10	1.22	1.08	.61	.07			4.98
Minnidoka South				.04	.28	.58	.77	.61	.35	.02			2.67
Huntley				.005	.07	.20	.49	.42	.09				1.28
Milk River				.05	.18	.11	.35	.07	.02	.04	.005		.82
Sun River					.12	.37	.53	.33	.08	.001			1.44
Lower Yellowstone					.04	.35	.70	.26	.05	.015			1.43
North Platte					.16	.48	.64	.56	.38				2.22
Truckee--Carson			.06	.37	.58	.55	.57	.40	.28	.08	.01		3.25
Carlsbad	.007	.03	.10	.40	.41	.35	.36	.39	.21	.10	.06		2.42
Rio Grande	.03	.24	.49	.68	.82	.87	.65	.51	.67	.26	.05	.09	5.17
Umatilla	.05	.76	1.17	1.42	1.35	1.35	.72	.05	.01				6.88
Klamath				.003	.18	.37	.30	.22	.04				6.68
Belle Fourche					.01	.31	.45	.17	.12	.005			1.06
O'Kanogan				.005	.25	.51	.57	.64	.11	.01	.01		2.13
Sunnyside				.26	.53	.53	.59	.54	.35	.24			3.04
Tieton					.41	.46	.51	.52	.25				2.15
Yakima				.05	.28	.46	.64	.41	.18	.05	.14		2.11
Average	.055	.26	.36	.27	.42	.57	.61	.46	.27	.11	.13	.09	3.11